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STATE OF NEVADA

DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

DIVISION OF WATER RESOURCES

WATER RESOURCES BULLETIN NO. 44

PUMPING AND GROUND-WATER STORAGE DEPLETION IN LAS VEGAS VALLEY, NEVADA, 1955-74

By

JAMES R. HARRILL

Prepared cooperatively by the

United States Department of the Interior

GEOLOGICAL SURVEY

1976

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CONVERSION FACTORS

For those readers who may prefer to use metric units rather than English units, the conversion factors for terms in this report are listed below:

English unit	Metric unit	Multiplication factor to convert from English to metric quantity
Feet (ft)	Meters (m)	.3048
Miles (mi)	Kilometers (km)	1.609
Acres	Square meters (m^2)	4,047
Square miles (mi^2)	Square kilometers (km^2)	2.590
Acre-feet	Cubic meters (m^3)	1,233
Gallons per minute (gpm)	Liters per second (l/s)	.06309
Gallons per day/ft	Meters squared/day (m^2/day)	.01242
Gallons per day/ft^2	Meters/day (m/day)	.04074

PUMPING AND DEPLETION OF GROUND-WATER STORAGE IN LAS VEGAS VALLEY, NEVADA, 1955-74

By James R. Harrill

ABSTRACT

During the 18-year period 1955-72, about 1,140,000 acre-feet of ground water was pumped from the valley-fill reservoir in Las Vegas Valley. This resulted in substantial water-level decline in the northwestern part of the valley where pumping was concentrated. Maximum net decline was about 180 feet. Much smaller declines occurred in the central valley, and water levels rose slightly in the southeastern part of the valley. The pumping resulted in about 68,000 acre-feet of water from compacted deposits in areas of subsidence and caused storage depletions of about 470,000 acre-feet in the principal aquifers, about 130,000 acre-feet from the near-surface reservoir, and about 35,000 acre-feet from consolidated rocks adjacent to the valley--a total depletion (including water derived from compacted deposits) of some 700,000 acre-feet.

The first year of full operation for the Southern Nevada Water Project was 1972. Large-scale importation of water resulted in annual pumpage declining from about 85,000 acre-feet in 1971 to about 70,000 acre-feet in 1972. By 1974, facilities were operating at near capacity, and additional demands were satisfied by increasing ground-water pumpage to 78,000 acre-feet. Water levels recovered temporarily in 1972, but by March 1975, annual water-level decline in the principal aquifers exceeded 10 feet per year in nearly 25 square miles of the northwestern part of the valley. Overdraft on the principal aquifers in 1974 was about 36,000 acre-feet, even though the estimated perennial yield, considered to be nearly equivalent to the annual natural recharge, had been augmented by the 10,000 acre-feet per year of secondary recharge from lawns, golf courses, parks, irrigated farms, and parts of Las Vegas Wash downstream from sewage treatment plants. The sustained yield ultimately possible will depend on how much the perennial yield of the natural system (about 25,000 acre-feet per year) can be supplemented by secondary recharge. Uncertainties involving maintenance of acceptable water quality and the success of proposed artificial recharge projects will have to be resolved before firm estimates of future yield can be made.

INTRODUCTION

This study, made in cooperation with the Nevada Department of Conservation and Natural Resources, evaluates some effects of large ground-water withdrawals during the period 1955-74 on the depletion of ground-water storage in Las Vegas Valley. The study, which is a followup of the one made by Malmberg (1965), was designed to evaluate effects of overdraft on ground-water storage and to document the initial response to variations in pumpage associated with importation of large quantities of water by the Southern Nevada Water Project.

Location and General Features

Las Vegas Valley encompasses about 1,564 square miles in Clark County, Nev. The area discussed in this report conforms with boundaries of the Las Vegas Valley hydrographic area designated by Rush (1968) and is slightly smaller than the area covered in a previous study by Malmberg (1965). Boundaries and general features of the study area are shown in figure 1.

The highest point in the area is Charleston Peak with an altitude of 11,918 feet. The lowest point is where Las Vegas Wash flows out of the area, altitude about 1,450 feet.

Most of the valley's water supply is generated from precipitation which falls on the Spring Mountains and Sheep Range. At the southern end of the valley (Glancy, 1968, p. 30). surface-water outflow occurs through Las Vegas Wash. Ground-water outflow, occurring as underflow in Las Vegas Wash, is very small. .

The cities of Las Vegas, North Las Vegas, and Henderson are in the valley. These urban areas are surrounded by densely populated suburbs. A population distribution map of Nevada (Bradhurst, 1972) shows the population of Las Vegas Valley to have been slightly more than 260,000 persons in 1970. Significant additional transient population is maintained because of the area's gaming and entertainment industry.

Purpose and Scope

The objectives of this study are: (1) to determine the distribution and magnitude of storage depletion since the last major study in 1955 (Malmberg, 1965); (2) to study effects of decreased pumpage, resulting from the increased use of imported water, on the ground-water reservoir; (3) to evaluate whether recharge from imported water is significantly augmenting the ground-water supply; and (4) to refine estimates of specific yield and specific storage of the alluvial deposits insofar as data permit.

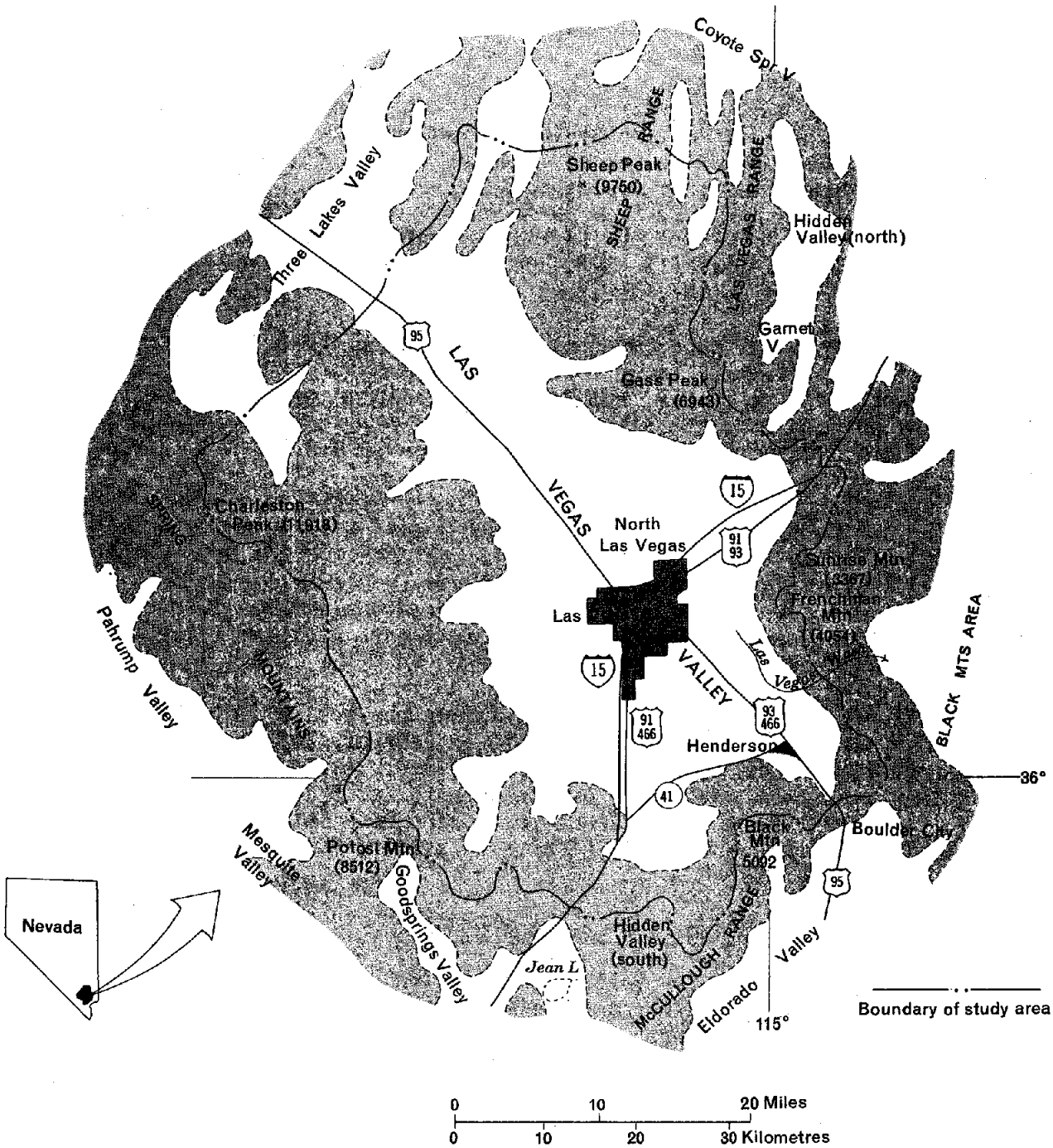


Figure 1.--Location and general features of study area; light gray shading indicates mountain areas, dark gray indicates urban areas.

To accomplish these objectives, the project was divided into two phases: The collection of basic data; and an analysis and interpretation. Data collection began in February 1971 when measurements of the seasonal high water levels were made in nearly 200 wells. Similar measurements were also made each year in 1972-75. In addition to water levels recorded by the U.S. Geological Survey, water-level measurements were obtained from the State Division of Water Resources, the Las Vegas Valley Water District, Nellis Air Force Base, and the Desert Research Institute. The distribution of annual pumpage was compiled from an inventory made by the State Division of Water Resources. Data through 1974 were compiled and published in three open-file data reports (Harrill, 1972, 1973, and 1974). Data collected in 1975 are included in a summary data report (Harrill, 1975).

Analysis of the various components of the ground-water system and the steps taken in the analysis, are discussed in appropriate sections of this report. Results of the initial analysis were incorporated into a digital model of the principal aquifers in the reservoir. The model was then used to refine the analysis of storage depletion since 1955.

The analysis phase of the project entailed preparing a water budget for the 18-year period 1955-72. The 18-year budget period was selected because (1) 1972 was the first year of full operation of the Southern Nevada Water Project, and (2) observations of land subsidence were available for approximately the same period. The budget period was divided into two subperiods, 1955-62 and 1963-73, to allow for a more detailed evaluation than possible when working with one period.

The net effects of seasonal pumping during the period 1955-72 were determined by evaluating measurements made in February 1955 and February 1973. An evaluation of net change in ground-water levels is based on measurements made when conditions are least affected by pumping, which usually is in the late winter of each year. The measurements in February 1973 largely reflect the residual effects of pumping during the previous spring, summer, and fall (1972).

Numbering System for Wells

The numbering system for wells listed in this report is based on the rectangular subdivision of the public lands, referenced to the Mount Diablo base line and meridian. It consists of three units: The first is the township south (S) of the base line; the second unit, separated from the first by a slant, is the range east of the meridian; the third unit, separated from the second by a dash, designates the section number. The section number is followed by letters that indicate the quarter section, quarter-quarter section, and so on; the letters a, b, c, and d designate the northeast, northwest, southwest, and southeast quarters, respectively. A number following the letters indicates the sequence in which the well was recorded in the designated area. For example, well S21/60-15abc1 is the first well recorded in the SW¼NW¼NE¼ section 15, T. 21 S., R. 60 E. Township and range numbers are shown along margins of the figures.

Acknowledgments

Appreciation is expressed for the cooperation of local residents in supplying data and permitting access to their wells for water-level measurement. Pumpage inventories, well logs, and water-level data on selected wells were obtained from the Las Vegas office of the State Division of Water Resources. The Las Vegas Valley Water District, the City of North Las Vegas, Nellis Air Force Base, the Desert Research Institute, and the Clark County District Health Department also provided valuable information on water levels and well construction. The following Geological Survey personnel provided significant assistance in the preparation of this report: Joseph Johns, David Wood, Louise Davis, and Marjorie Thielke. The digital model was tested at the State Computer Facility in Carson City.

GENERALIZED GEOLOGY

Lithologic Units

For the purpose of this report, the principal lithologic units in Las Vegas Valley were divided into two major groups on the basis of their hydrologic properties: (1) Unconsolidated and semiconsolidated deposits which form the valley fill; they are highly porous, and the coarse-grained beds transmit water readily. (2) Consolidated rocks which compose the mountains and underlie the valley fill; they have low porosity and permeability, and do not readily transmit water except where highly fractured or where fractures in carbonate rocks have been enlarged by solution. Six lithologic units are described in table 1; descriptions are based on the work of Maxey and Jameson (1948), Longwell and others (1965), Tabor (1970), and Price (1966). Areal distribution of the units is shown in figure 2.

Structural Features

The present geologic structure of the area is largely the result of thrust faulting in late Mesozoic time and normal and strike-slip faulting of Tertiary time. Consolidated rocks in the mountains surrounding Las Vegas Valley have been complexly folded and faulted. These features generally are internal to the consolidated rock masses and have only minor effects on the hydrology of the valley-fill ground-water reservoir. Consequently, they are not discussed in this report.

The largest structural feature in the valley area is the Las Vegas Valley shear zone, which traverses the northern part of the area (fig. 2). The fault is a regional feature. It has an estimated right lateral displacement of about 30 miles (Mindling, 1971, p. 33) and extends well beyond the boundaries of the valley.

Table 1.--*Principal lithologic units*

Age		Unit	Thickness (feet)	Lithology	Occurrence	General hydrologic properties
QUATERNARY	Pleistocene and Holocene	Surficial deposits	50±	Unconsolidated gravel, sand, silt, and clay.	Occurs throughout area of valley fill. Exposures not continuous but are limited to areas of Holocene and Late Pleistocene deposition. On alluvial fans, unit consist of stream-channel and slope-wash deposits. In lower parts of valley, unit occurs as fairly extensive deposits of sand, silt, and gravel. Included with alluvium in figure 2.	Generally above the zone of saturation on alluvial fan. In the southeast part of valley, saturated deposits may form a thin water-table aquifer. Westphal and Nork (1972, p. 1) estimated the average horizontal hydraulic conductivity of these deposits in the Henderson-East Las Vegas area to be about 400 gpd/ft^2.
QUATERNARY	Pleistocene	Valley fill: Lake and playa deposits (includes Las Vegas Formation in fig. 2)	300±	Predominately clay, silt, and fine sand. Contains some regular, thin-bedded layers of sand and gravel.	Exposed at base of alluvial fans along west side of valley; as prominent lake-bed deposits at northwest end of study area; and as irregularly exposed deposits in central part of valley. Well logs indicate upper valley-fill deposits in central part of valley commonly consist of a sequence of silt, clay, and caliche. Figure 2 shows extent of Las Vegas Formation as mapped by Longwell and others (1965) and Price (1966).	When saturated, fine-grained deposits may store appreciable quantities of water but have low permeability and transmit water poorly. Unit acts as a confining layer. When water is removed from storage, compaction and land subsidence may result. Unit yields some water to domestic wells.
QUATERNARY	Pleistocene	Valley fill: Fanglomerate and valley-floor deposits	1,000±	On alluvial fan, predominately gravel and and sand with some silt and clay. Deposits may be well cemented with caliche. On valley floor, generally silt and clay with interbedded sand and gravel. Lithology similar to overlying lake-bed and playa deposits. Upper contact arbitrarily located at top of first significant water-producing sand or gravel.	Occurs throughout area of valley fill. Exposed as alluvial fans but generally concealed by surficial deposits or lake and playa deposits on valley floor.	Gravel deposits along lower parts of fans transmit water readily and form most productive aquifers in valley. Finer gravel deposits in central part of valley produce water less readily but provide adequate supplies for domestic wells and moderate-capacity industrial and public supply wells. Heavy pumping in area of fine-grained deposits may result in land subsidence.
TERTIARY		Muddy Creek Formation	4,000±	Silt, clay, and sandstone, with some lenses of pebble conglomerate. Locally contains salt and gypsum beds. Interstratified basalt flows in some areas.	Forms prominent bluffs in southeast part of valley. Also exposed north and south of Frenchman Mtn. Probably underlies Quaternary valley-fill deposits throughout much of valley.	Low-permeability deposits which do not readily yield water to wells. Gypsum and salt may affect ground-water quality.
TERTIARY		Volcanic rocks	--	Complex assemblage of andesitic lava flows, volcanic breccia, and associated rocks. Includes some intrusive porphyritic rocks. Not differentiated.	Southwest of Las Vegas Valley floor, in McCullough Range and River Mtns. Includes small area of intrusive rocks in the McCullough Range.	Impermeable except where highly fractured; probably forms barrier to ground-water movement.
TRIASSIC TO CRETACEOUS	Consolidated rocks	Noncarbonate sedimentary rocks	3,500-8,000	Sandstone, shale, and conglomerate. Some interbedded limestone and gypsum.	Exposed on Frenchman Mtn. and along southwest border of area. Includes Thumb Formation, Aztec Sandstone, Chinle Formation, and Moenkopi Formation.	Generally impermeable; may transmit moderate amounts of water where fractured. Gypsum may affect sulfate content of ground water.
PRECAMBRIAN TO PERMIAN	Consolidated rocks	Gypsiferous sedimentary rocks	2,000±	Limestone, dolomite, shale, conglomerate, and sandstone. Sequence contains significant amounts of gypsum.	Exposed on Frenchman Mtn. and along southwest border of area. Includes Kaibab Limestone, Toroweap Formation, and red beds.	Generally impermeable; may transmit moderate amounts of water where fractured, or where fractures have been enlarged by solution. Gypsum may affect sulfate content of ground water.
PRECAMBRIAN TO PERMIAN	Consolidated rocks	Non-gypsiferous sedimentary rocks	20,000±	Limestone, dolomite, shale, sandstone, and quartzite.	Exposed on Frenchman Mtn., the Sheep Range, and Spring Mtns. Includes Bird Spring Formation, Monte Cristo and Sultan Limestones, Lone Mountain and Ely Springs Dolomites, Eureka Quartzite, Pogonip Limestone, Chisholm Shale, Lyndon Limestone, Pioche Shale, and Tapeats Sandstone.	Generally impermeable except where solution has caused a secondary enlargement of joints and fractures. May transmit large quantities of ground water in these areas.

Presumably much of the valley is bounded by normal faults; however, direct evidence of faulting, if present, is concealed by Quaternary deposits. Only one fault of this type is well exposed. It borders the southwest flank of Frenchman Mountain.

Several prominent escarpments are present in the central part of the valley (fig. 2). Maxey and Jameson (1948, p. 70) postulated that they mark the course of near-surface compaction faults and may be nontectonic; they may have been caused by differential compaction of fine- and coarse-grained sediments in areas where there is a rapid lateral change in grain size. One exception, the Eglington scarp, is nearly straight and transects both alluvial fan gravels and finer grained sediments. Its origin is probably tectonic and related to the Las Vegas shear zone (Mindling, 1971, p. 33). This feature apparently formed about 14,000 years ago (Haynes, 1967, p. 78).

VALLEY-FILL RESERVOIR

The valley-fill ground-water reservoir is composed of alluvium and the Muddy Creek Formation (table 2), which partly fill the structural depression underlying Las Vegas Valley. These deposits contain the most productive aquifers in the area and have been the source of virtually all large-scale ground-water development.

Extent and Boundaries

The valley-fill reservoir occupies the central part of Las Vegas Valley. It has a surface area of about 550 square miles. Consolidated rock surfaces of the adjacent mountains and their subsurface extensions form the lateral and bottom boundaries of the reservoir. Malmberg (1965, p. 21) reported that an oil test well, S21/62-22dd1, penetrated approximately 3,050 feet of sediment that resembled the Muddy Creek Formation before encountering bedrock. Tabor (1970, p. 17) reports that in the Kratter no. 68 well, S21/61-10bd, the Muddy Creek Formation was overlain by 950 feet of Quaternary deposits and was assigned a thickness of 4,000 feet, based on interpretations of geophysical logs. Thus, total thickness of valley fill may be on the order of several thousand feet throughout much of the valley; however, the Quaternary alluvium which comprises roughly the upper 700 to 1,000 feet of valley fill contains the most productive aquifers, and is that part of the valley-fill reservoir most affected by pumping.

Figure 3 shows the approximate areal extent of the reservoir. Figure 3 also shows contours of gravity anomalies which give rough indications of the reservoir's subsurface configuration. The precise configuration of the bottom surface cannot be determined from existing data. Gravity contours do not indicate a simple, symmetrical, depression. The highest anomalies and the areas with the greatest contrast between bedrock and valley fill are at the north end of the valley. This corresponds with the approximate location of the Las Vegas shear zone (fig. 2). Anomalies at the south end of the valley are less pronounced because the density contrast between bedrock and valley-fill areas is not so great. The less pronounced anomaly

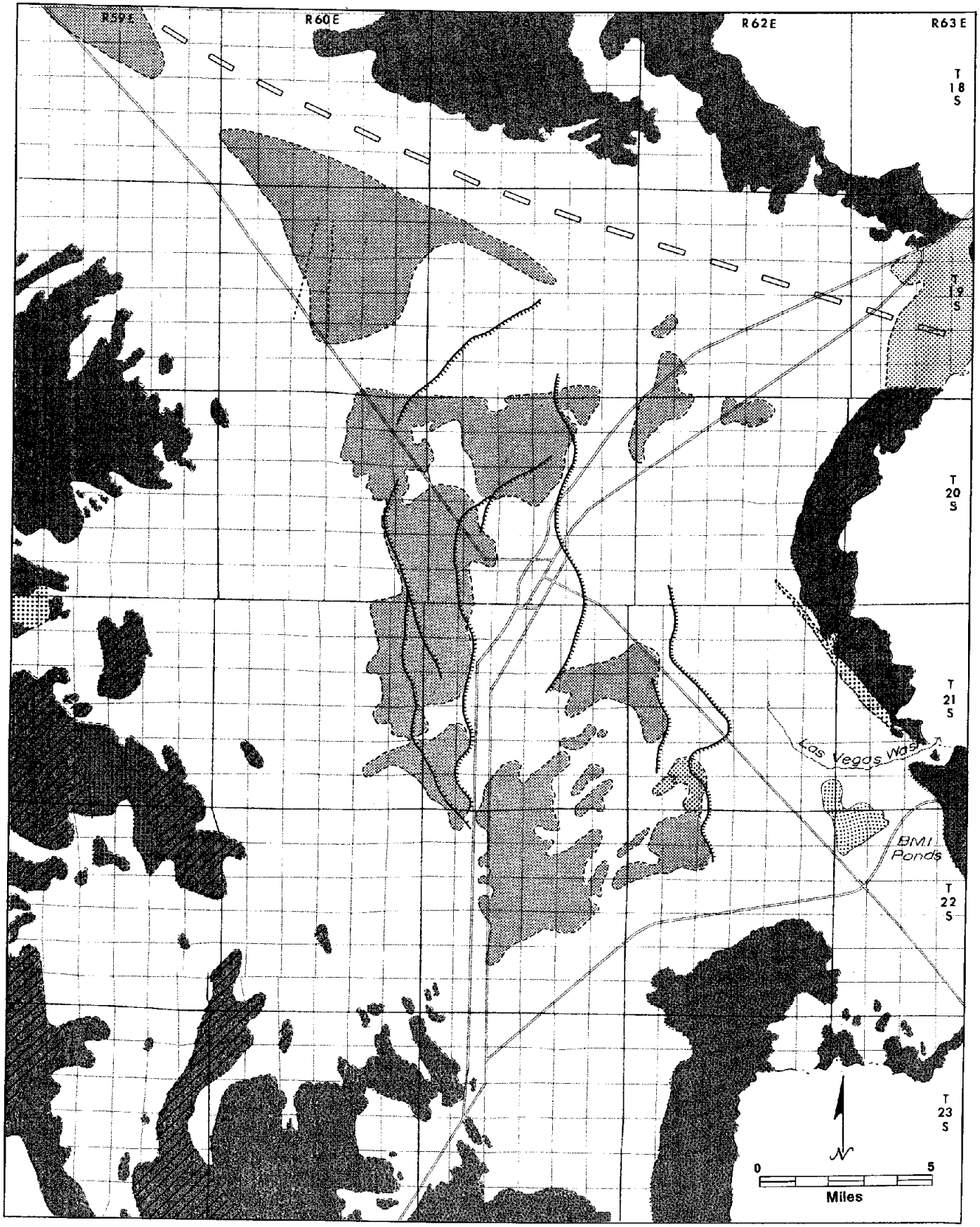


Figure 2.--Generalized geology.

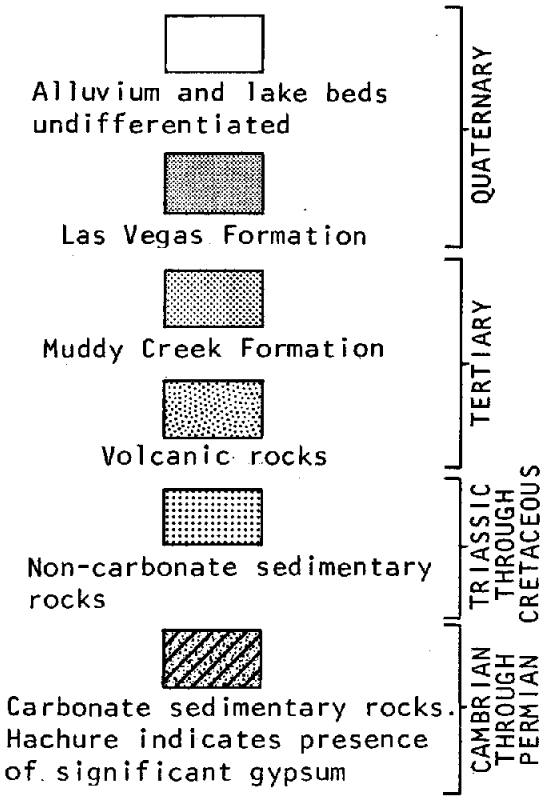
at the south end may be due in part to the subsurface configuration of the reservoir and in part to variations in density contrast between valley-fill deposits and underlying consolidated rocks.

Subdivisions

Detailed stratigraphy of the valley-fill reservoir is complex, and individual beds of widespread extent are not common. To analyze the valley-fill reservoir, it was necessary to group the zones having similar hydraulic characteristics.

Three rather indistinct zones of artesian aquifers--a shallow, a middle, and a deep zone--were described by Maxey and Jameson (1948, p. 81-82). In addition, a shallower zone of ground water is locally termed "surface water" (Maxey and Jameson, 1948, p. 81). It is in part unconfined, but more commonly is under slight artesian pressure. Malmberg (1965, p. 24) described the aquifers containing "surface water" as the near-surface zone of aquifers or the near-surface reservoir. In this report, the various zones are grouped into two categories, the near-surface reservoir and the principal aquifers.

EXPLANATION



Contact

Scarp, (Maxey and Jameson, 1948)

Fault

Lineament (spring mounds)

Basin boundary

Geology after: Longwell and others (1965) and Price (1966). Area shown for Las Vegas Formation is aggregate area as mapped in both reports. Future studies may reveal more extensive deposits

Figure 2.--Continued

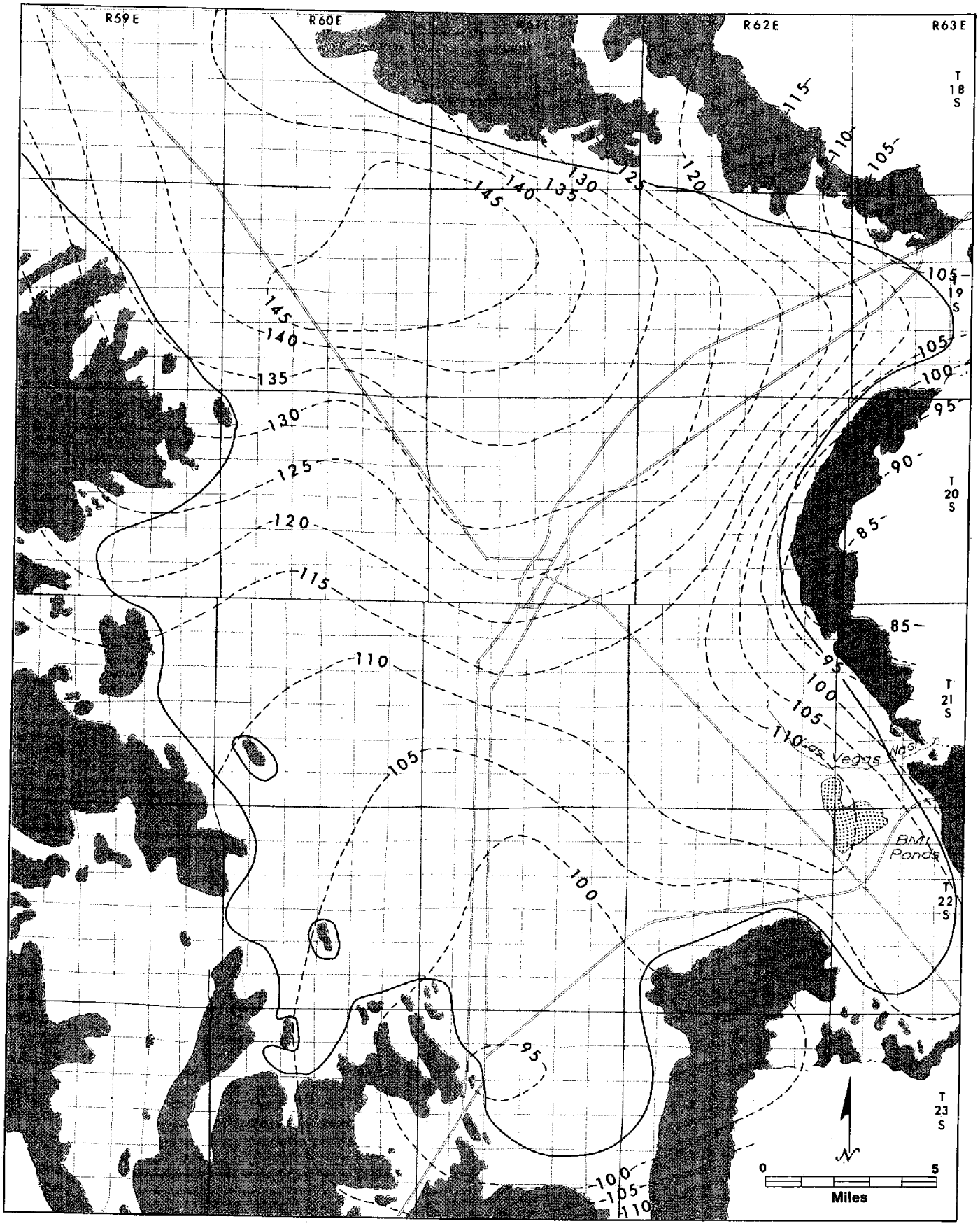


Figure 3.--Approximate areal extent of valley-fill reservoir and contours of simple Bouguer anomaly.

The principal aquifers include all the shallow, middle, and deep zones (as defined by Maxey and Jameson, 1948, p. 81 and 82) which are penetrated or significantly affected by large-capacity wells. These aquifers supply nearly all of the water pumped from wells and are the units which will be most thoroughly evaluated in this report. They are distributed throughout the valley fill. The upper boundary is formed by the base of the near-surface reservoir or by the water table where the near-surface reservoir is not well defined. The lower boundary is poorly defined; however, most large-capacity wells are less than 1,100 feet deep.

The near-surface aquifers are not well defined in areal extent or depth, and except where they occur as semiconfining deposits above the artesian aquifers, they are difficult to delineate because they do not compose a distinct lithologic or hydrologic unit (Malmberg, 1965, p. 24). A peg model constructed from drillers' logs of 145 selected wells was used to approximate the general distribution and thickness of that part of the near-surface reservoir which is semiconfining. Figure 4 shows the approximate distribution and thickness of the semiconfining layer determined from the peg model. In the southeastern part of the valley, semiconfining beds at some locations are overlain by a thin layer of more permeable material. In the central part of the valley, no sharp lithologic change is apparent between semiconfining beds and the underlying aquifers. The lower boundary of the semiconfining beds was placed at the first indication of significant water-bearing material. Thus, in some areas, the only difference in the gross character of the confining beds and underlying deposits is the presence of a few horizons of sand or gravel in the lower deposits. Consequently, near-surface reservoir thicknesses indicated in excess of 300 feet in figure 4 may be inaccurate, reflecting inadequate lithologic information in well logs. Outside the near-surface reservoir boundary shown in figure 4, layers of caliche provide some resistance to vertical movement of water, which probably results in a surficial zone of unconfined ground water near the water table. This zone is underlain by deposits in which the water may be partly confined.

Flow within the near-surface reservoir is complex, and a detailed analysis is beyond the scope of this report. Analysis is limited to evaluation of those parameters necessary to estimate inflow to or outflow from the principal aquifers.

EXPLANATION

Valley-fill

Consolidated rocks

Contact

Basin boundary

Approximate boundary of valley-fill reservoir

110

Line of equal simple Bouguer anomaly. Interval 5 milligals. (After Kane and Carlson, 1964)

Figure 3.--Continued

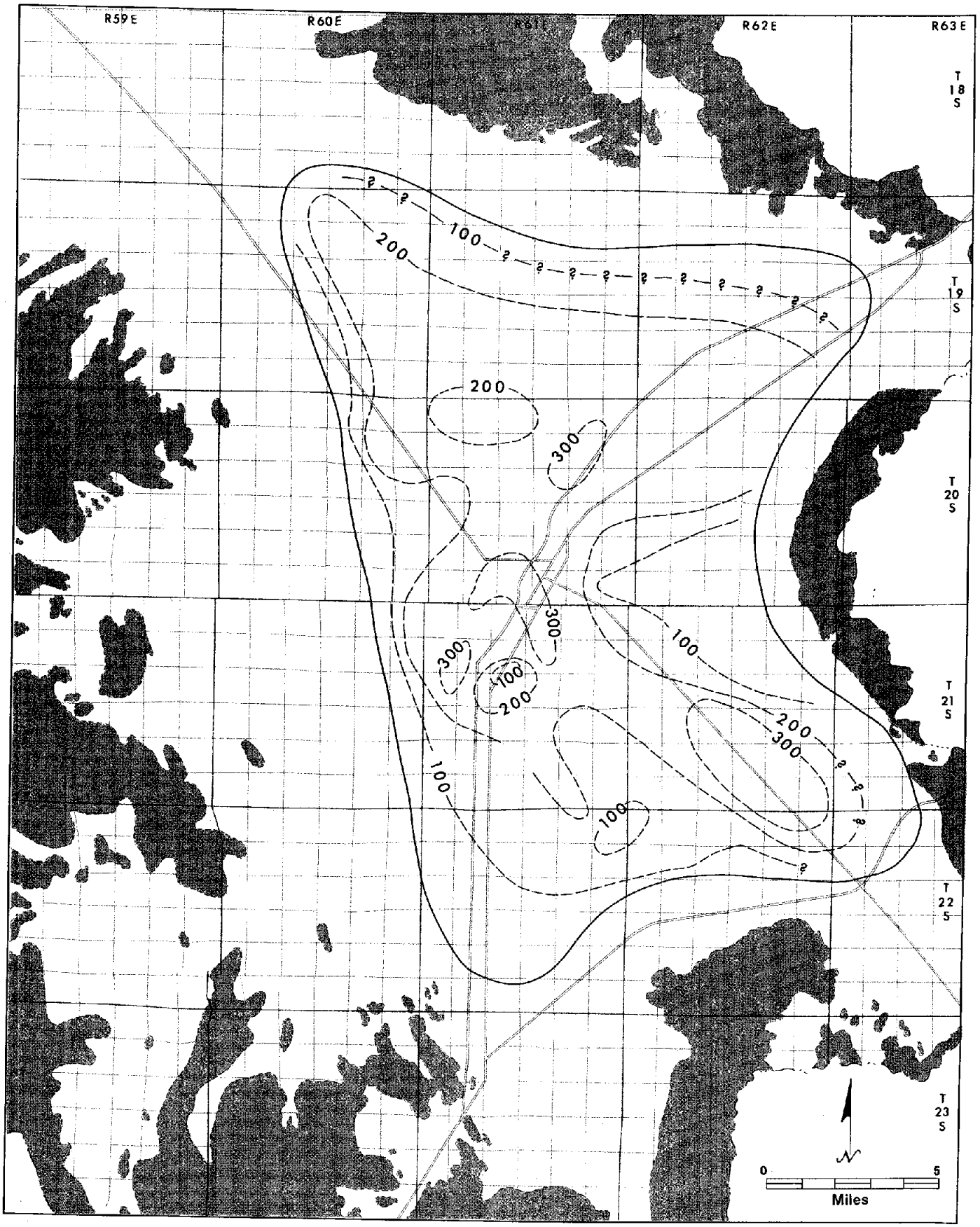


Figure 4.--Approximate extent and thickness of near-surface reservoir.

Distribution of Sand and Gravel

Deposits of sand and gravel commonly yield most of the water to wells in the valley. Knowledge of the overall distribution of these deposits provides generalized information about variations in water-bearing properties of the valley fill.

Domenico and others (1964) evaluated numerous drillers' logs of wells in the valley and collected lithologic samples from several deep wells. Using this information they devised a standard geologic interpretation of drillers' terminology and estimated the percentage of sand and gravel in the interval between 200 and 700 feet below land surface. This interval contains the most heavily pumped zones of the principal aquifers. They published their results on a map which is reproduced with minor modifications in figure 5. To provide a rough comparison with the near-surface reservoir, a similar map was prepared for the depth interval of 0-200 feet using the same standard interpretation (Domenico and others, 1964, table 1) and drillers' logs of 205 selected wells; this map also is shown in figure 5.

Both maps show sand and gravel to be abundant around the western and southern margins of the valley and sparse in the central part of the valley. The area where sand and gravel is sparse and clay and silt predominate is more extensive in the interval 0-200 feet than in the deeper interval. This may be visualized by comparing the shaded areas (less than 30 percent sand and gravel) on each map in figure 5. The area of less than 30 percent sand and gravel in the interval 0-200 feet corresponds with thicker areas of the near-surface reservoir shown in figure 4. Not shown in figure 5 are areas where gravel is cemented by caliche or other materials. Cementation tends to reduce the ability of these deposits to store and transmit water but the degree to which this has occurred could not be determined.

EXPLANATION

Valley-fill

Consolidated rocks

Contact

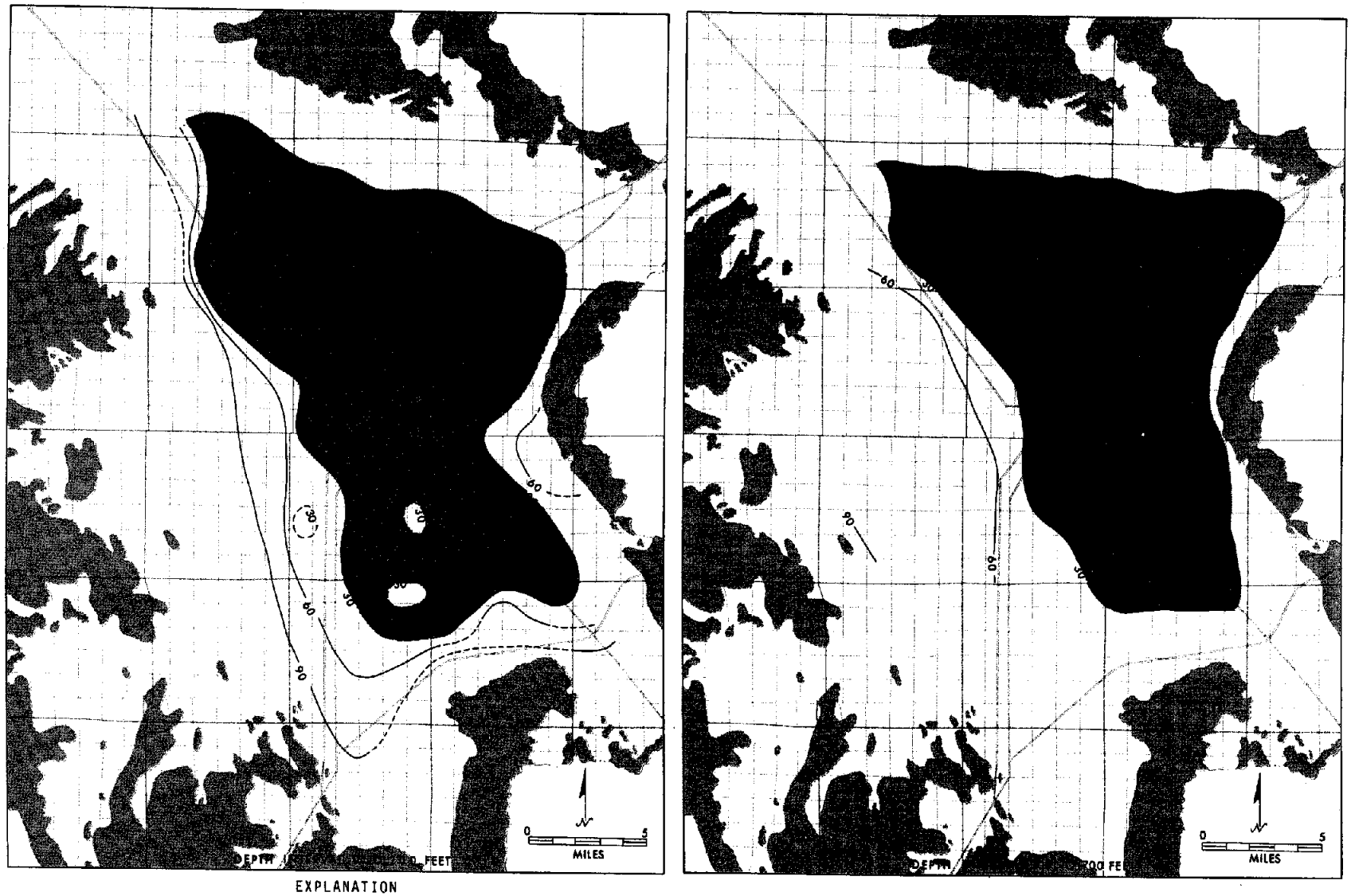
Basin boundary

Approximate boundary of near-surface reservoir as recognized in this study

----------100----------

Generalized line of equal thickness of near-surface reservoir. Interval 100 feet. Questioned where position doubtful

Figure 4.--Continued



EXPLANATION

Valley-fill

Consolidated rocks

Contact

Basin boundary

30 Generalized line of equal percent sand and gravel. Interval 30 percent. Shading indicates area less than 30 percent

Note: Data for depth interval 200-700 feet from Domenico and others, 1964, fig. 8

Figure 5.--Distribution of sand and gravel in two depth intervals of valley fill.

Selected Hydraulic Properties

Principal Aquifers

Transmissivity.--Transmissivity is a measure of the ability of an aquifer to transmit water. It is dependent on the permeability and thickness of the water-bearing materials. Transmissivities may be determined from aquifer tests or estimated from specific capacities of wells. Specific capacities are expressed as well yield, in gallons per minute, per foot of drawdown. Properly designed wells in deposits with high transmissivities have higher specific capacities than wells tapping deposits with low transmissivities.

Figure 6 shows the approximate distribution of transmissivity in the principal aquifers in Las Vegas Valley. Point values show transmissivities determined by pumping tests (Malmberg, 1965, p. 42) and values estimated from specific capacities reported in drillers' logs. Values range from about 1,000 to about 300,000 (gal/d)/ft. The lower values may be affected by well inefficiencies, and the actual transmissivity in these areas may be higher than indicated in figure 6. Even taking this into account, variations of about two orders of magnitude are present within the valley-fill reservoir. The areal distribution of the zones of transmissivity shown in figure 6 approximate those used in a digital model of the principal aquifers (discussed in a later part of this report). These values allowed a satisfactory simulation of natural conditions and response to pumping stress. They are commonly higher than point values estimated from specific capacities because these values may be affected by well inefficiencies.

Specific yield.--The specific yield of a deposit is the ratio of (1) the volume of water which, after saturated, the deposit will yield by gravity, to (2) its own volume, usually expressed as a percentage (Meinzer, 1923, p. 26). Specific yields of alluvial deposits range from about 30 percent in well-sorted sand or gravel to less than 5 percent in compacted clay or deposits with extensive caliche development. Where unconfined conditions predominate in the principal aquifers, water-bearing sediments are primarily sand and gravel. These deposits typically have specific yields between 20 and 25 percent; however, drillers' logs indicate extensive areas where pore spaces have been filled to some degree by caliche or other cementing material. The degree of cementation and extent to which this process has affected specific yield varies. Consequently, the overall effect on specific yield could not be determined. Average specific yield may be on the order of 15 percent. However, because of long times required for complete drainage and the presence of perched water above clay and caliche zones, the storage depletion as of 1972 was probably somewhat less than if drainage equaled specific yield.

Storage coefficient.--The storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area, per unit change in head.

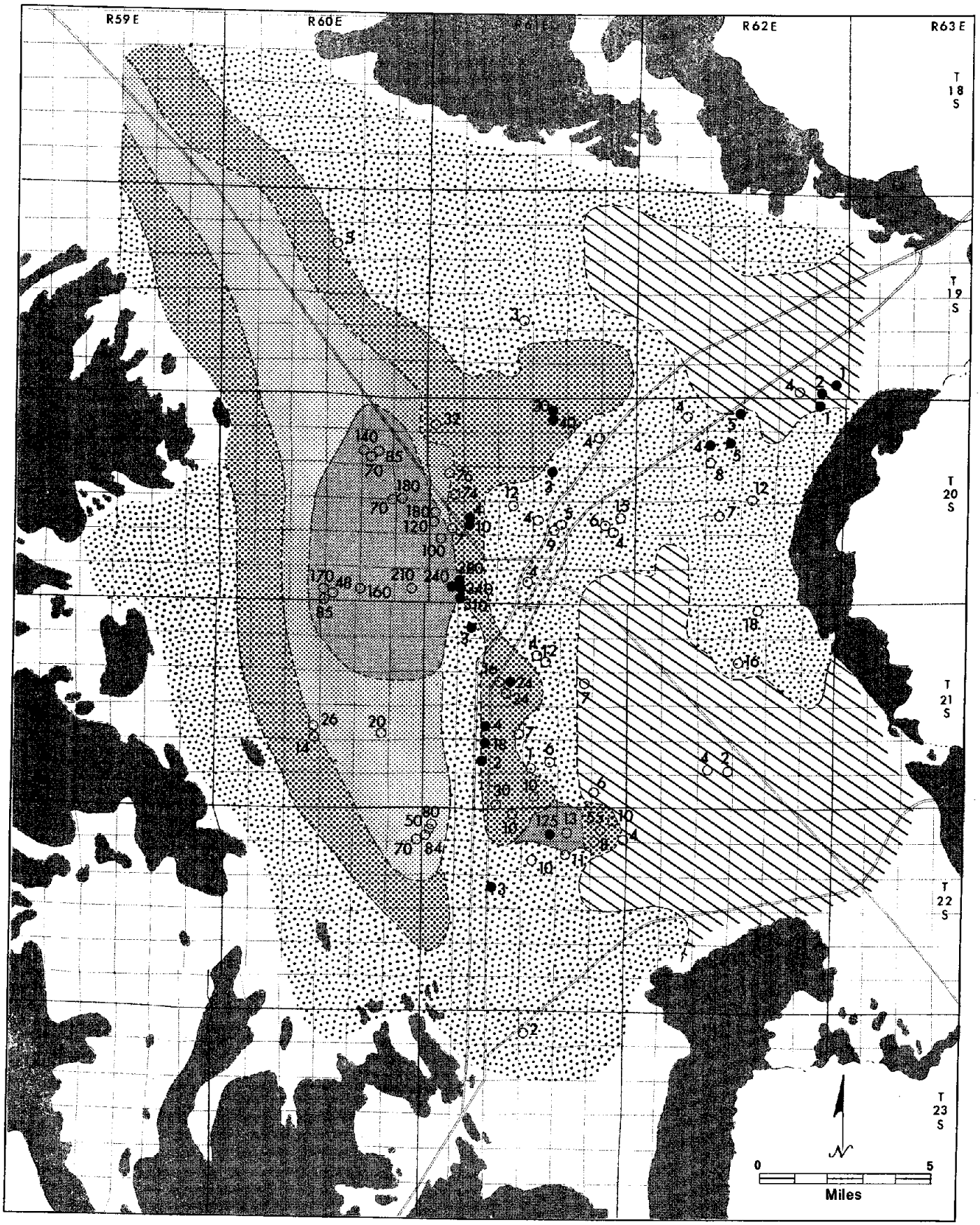


Figure 6.--Distribution of transmissivity, principal aquifers.

Where aquifers underlie a well-defined semiconfining bed, water removed from storage as a result of head decline comes from expansion of the water and compression of the aquifer (this excludes water derived from storage in the semiconfining layer). The storage coefficient of a confined aquifer may be approximately estimated by multiplying aquifer thickness, in feet, by 10^{-6}, (Lohman, 1972, p. 53). Thickness of the principal aquifers varies, but may average about 500 feet in the central valley. (Thicker accumulations occur along the western margin of the valley.) The estimated storage coefficient for this thickness would be about 0.0005. This is comparable with the values listed by Malmberg (1965, p. 42). However, a value of 0.001 is used in this report to allow for some inflow from underlying low-permeability beds. Where unconfined or semiconfined conditions predominate, the coefficient of storage increases with time. Initially the value is the same as for confined conditions, but as deposits slowly drain in response to pumping, the storage coefficient approaches the specific yield. Values used in this report are slightly less than the specific yield in order to allow for delayed drainage and for the probable development of localized bodies of perched ground water above beds of impermeable caliche or clay. Figure 7 shows the areal distribution of storage coefficient used in this report.

Near-Surface Reservoir

Hydraulic conductivity.--The hydraulic conductivity of a porous medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. For purposes of this study, only the vertical hydraulic conductivity of that part of the near-surface reservoir which occurs as a well-defined confining layer was estimated. Preliminary estimates were made at selected points on the basis of vertical hydraulic gradient, thickness of confining layer, and distribution of evapotranspiration. Most estimates were between 0.005 and 0.05 $(gal/d)/ft^2$. This range of values is in general agreement with laboratory determinations obtained for very fine-grained materials from other areas. The preliminary estimates were used to obtain an approximate distribution of vertical hydraulic conductivity, which was then refined after being incorporated into a digital model. Figure 8 shows the approximate distribution used in this study.

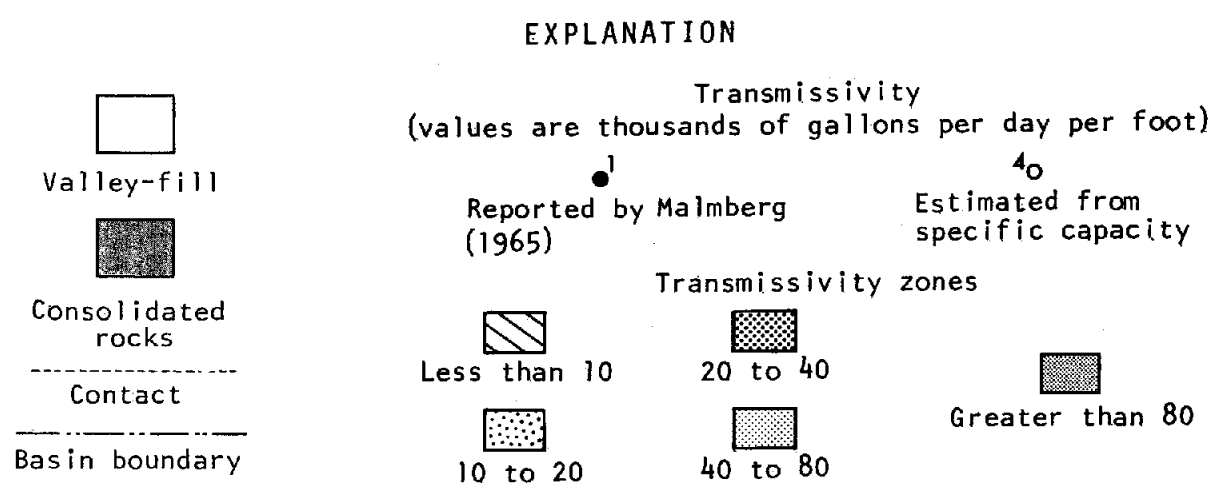


Figure 6.--Continued

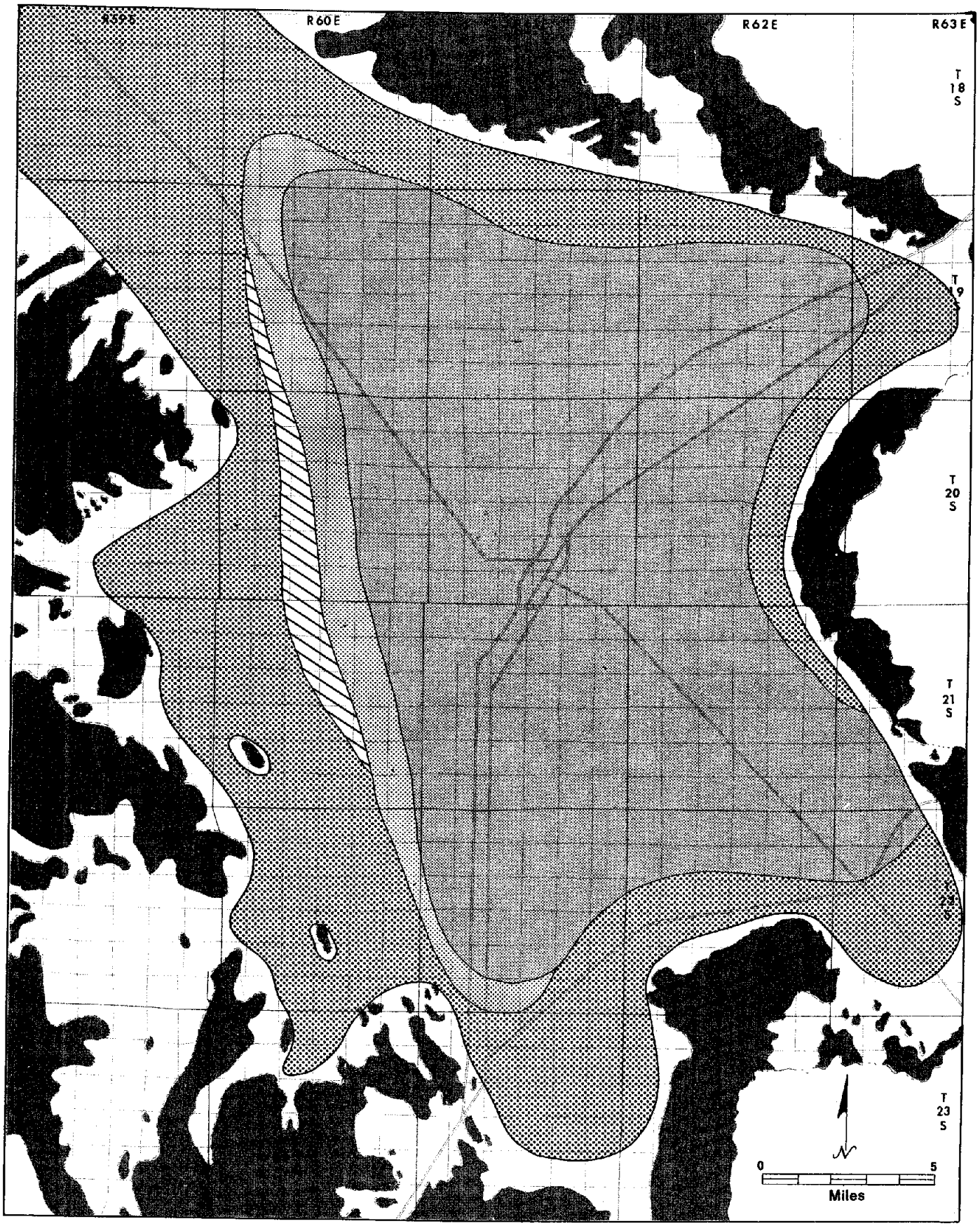


Figure 7.--Distribution of storage coefficient, principal aquifers.

Specific storage.--Specific storage is the volume of water released from or taken into storage per unit volume of porous medium per unit change in head (Lohman and others, 1972, p. 13). In more general terms, specific storage is one of the parameters which regulate the ability of a confining layer to release water from storage in response to declines in artesian head. Release of water from storage in confining beds may result in land subsidence where significant pumping is done in proximity to clay deposits. Comparison of known magnitudes of land subsidence with measured head declines and the approximate thickness of the confining layer suggests specific storage of the confining layer is on the order of 10^{-3} to 10^{-4}.

DEVELOPMENT, 1955-74

The period 1955-74 was one of rapid growth in Las Vegas Valley. Population increased from about 50,000 in 1955 to slightly more than 300,000 in 1974. This growth was accompanied by a corresponding increase in water requirements. Total use of water increased from about 57,000 acre-feet in 1955 to about 162,000 acre-feet in 1974. Sources of water in 1974 included about 78,000 acre-feet of pumped ground water, about 75,000 acre-feet of Colorado River water, and about 9,000 acre-feet of recycled wastewater (used mainly for irrigation and cooling purposes).

Ground-Water Pumpage

Estimates of total annual ground-water pumpage from the near-surface reservoir and principal aquifers during the period 1955-74 are listed in table 2. More than 95 percent of the pumpage is from the principal aquifers. Annual pumpage steadily increased to a maximum of 88,000 acre-feet in 1968. At that time, importation of Colorado River water became sufficient to compensate for new growth and allow for a slight decrease in pumping over the next several years. The first phase of the Southern Nevada Water Project became operational in 1971, and ground-water pumpage was reduced to about 70,000 acre-feet during the following 2 years.

EXPLANATION

Valley-fill

Consolidated rocks

Contact

Basin boundary

Storage computation boundary

Character of Reservoir	Storage Coefficient	Zone Designation
Artesian (leaky)	0.001	
Transitional	0.01 0.04	
Water table (delayed drainage)	0.13	

Figure 7.--Continued

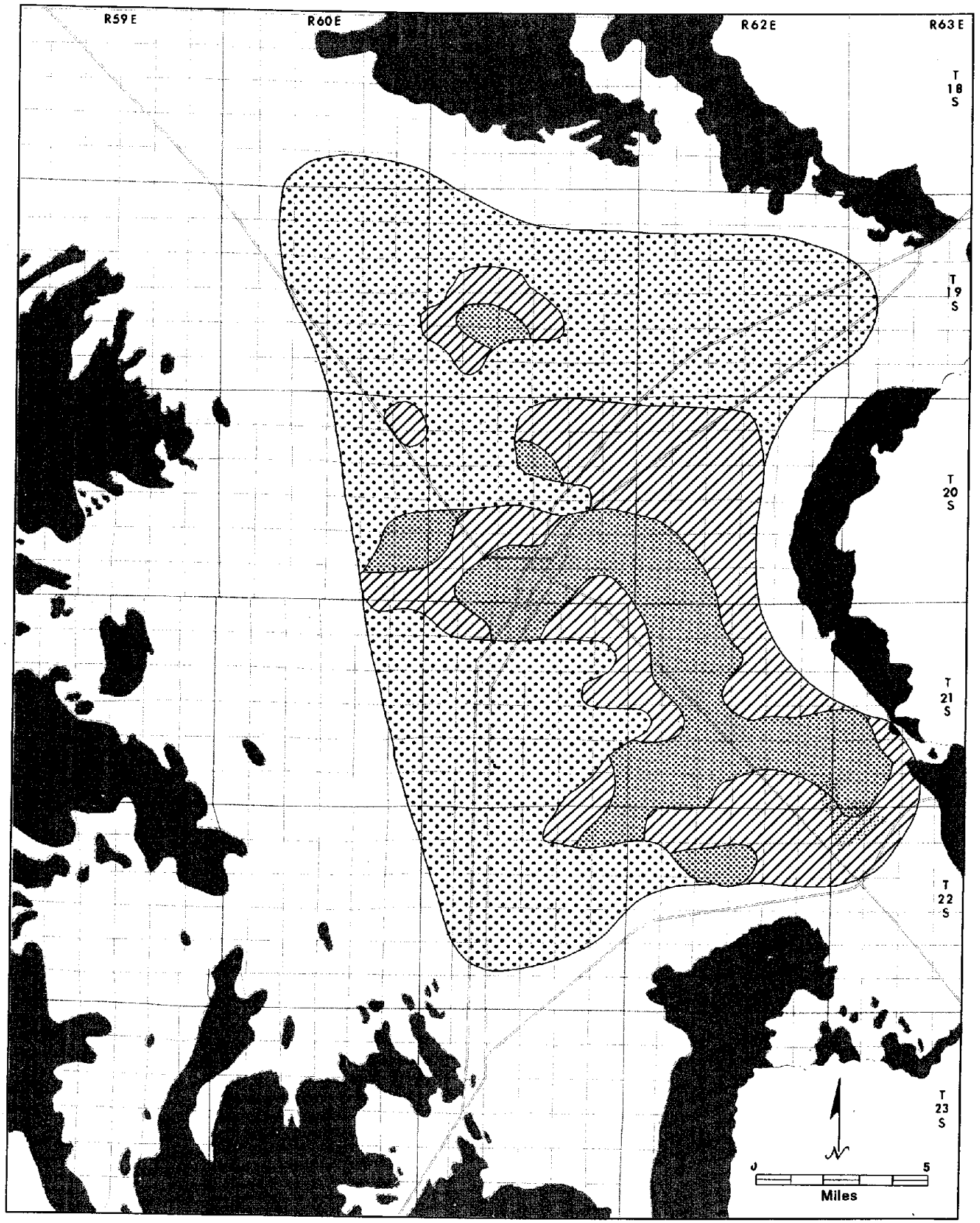


Figure 8.--Estimated distribution of vertical hydraulic conductivity in the near surface reservoir.

Location of pumping changed significantly between 1955 and 1974. Figures 9 and 10 show the distribution of pumpage in 1944 and 1973. Until about 1963, pumping increased in the central part of the valley; however, land subsidence became a problem and the major centers of pumping were shifted to the alluvial fans where local subsidence was not significant.

Importation of Colorado River Water

Prior to 1955 the city of Henderson and BMI (Basic Management, Inc.) were the only areas in the valley served by water imported from Lake Mead. In 1955 the Las Vegas Valley Water District began purchasing water from BMI for public-supply purposes. Use of imported water increased gradually until 1971, when the Southern Nevada Water Project became operational and large-scale importation of Colorado River water to the main part of the valley became possible. Table 3 summarizes Lake Mead imports to the valley during the period 1955-74. The second phase of the Southern Nevada Water Project is scheduled for completion in 1980. At that time imported water will probably become the principal source of supply in Las Vegas Valley.

RESPONSE TO DEVELOPMENT

During the 20-year period 1955-74, nearly 1,300,000 acre-feet of ground water was pumped from the valley-fill reservoir in Las Vegas Valley. Most of this pumpage came from the principal aquifers, which placed a large stress on this part of the reservoir system. The response was complex. It included head (water-level) changes and storage changes in the principal aquifers and near-surface reservoir, variations in the ground-water flow regimen, changes in phreatophyte densities, and land subsidence.

EXPLANATION

Valley-fill

Consolidated rocks

Contact

Basin boundary

Approximate boundary of near-surface reservoir

Zones of vertical hydraulic conductivity (values in gallons per day per square foot)

Less than 0.01

0.01 to 0.025

Greater than 0.025

Figure 8.--Continued

Table 2.--*Estimated ground-water pumpage, 1955-74* 1/

(Annual estimates rounded to nearest 1,000 acre-feet)

Year	Near-surface reservoir (acre-feet) 2/	Principal aquifers (acre-feet)	Total (acre-feet)
1955	1,000	39,000	40,000
1956	1,000	42,000	43,000
1957	1,000	43,000	44,000
1958	1,000	42,000	43,000
1959	1,000	45,000	46,000
1960	1,000	47,000	48,000
1961	2,000	50,000	52,000
1962	2,000	52,000	a 54,000
1963	2,000	57,000	a 59,000
1964	2,000	62,000	64,000
1965	2,000	71,000	73,000
1966	2,000	76,000	78,000
1967	2,000	79,000	81,000
1968	b 5,000	83,000	88,000
1969	6,000	81,000	87,000
1970	6,000	80,000	86,000
1971	6,000	79,000	85,000
1972	7,000	63,000	70,000
1973	7,000	63,000	70,000
1974	7,000	71,000	78,000
Total	64,000	1,200,000	1,300,000
Subtotals for selected study periods used in this report:			
1955-62	10,000±	360,000±	370,000
1963-72	40,000	730,000	770,000
1955-72	50,000±	1,090,000±	1,140,000

1. Based on pumpage inventories by the Nevada State Engineer.

2. Approximated as reported estimate of pumpage from nonpermit domestic wells.

a. Revised from previously published estimates (Harrill, 1974, table 2).

b. Marked increase due in part to a change in the method of estimating pumpage.

Table 3.--*Summary of imports from Lake Mead, 1955-74*

(From records of the Colorado River Commission)

	IMPORTS (in acre-feet per year)						
			Southern Nevada Water Project 1/				
Year	Las Vegas Valley Water District	City of Henderson and BMI	Las Vegas Valley Water District	Nellis Air Force Base	City of North Las Vegas	City of Henderson	Total, Las Vegas Valley
1955	428	16,255	0	0	0	0	16,683
1956	1,589	21,175	0	0	0	0	22,764
1957	1,247	16,778	0	0	0	0	18,025
1958	2,202	15,581	0	0	0	0	17,783
1959	1,079	15,450	0	0	0	0	16,529
1960	2,146	15,898	0	0	0	0	18,044
1961	3,334	15,773	0	0	0	0	19,107
1962	4,887	16,473	0	0	0	0	21,360
1963	6,407	18,084	0	0	0	0	24,491
1964	5,879	16,423	0	0	0	0	22,302
1965	3,596	16,298	0	0	0	0	19,894
1966	5,334	18,079	0	0	0	0	23,413
1967	4,651	18,794	0	0	0	0	23,445
1968	6,920	22,951	0	0	0	0	29,871
1969	9,558	24,021	0	0	0	0	33,579
1970	13,350	20,897	0	0	0	0	34,247
1971	6,120	19,687	14,544	284	454	0	41,089
1972	0	26,300	42,038	1,445	1,324	4	71,111
1973	0	19,345	48,674	1,276	2,341	1,735	73,371
1974	0	19,238	49,290	1,509	3,394	1,939	75,455

1. First water delivered on June 16, 1971.

Water-Level Changes

The principal response to development has been declines in water levels in wells throughout most parts of the principal aquifers. Declines have been greatest in areas adjacent to centers of pumping but declines of lesser magnitude are also occurring along peripheral parts of the reservoir. An exception to the trend of general decline occurs in the vicinity of Henderson and along parts of Las Vegas Wash in the southeast part of the

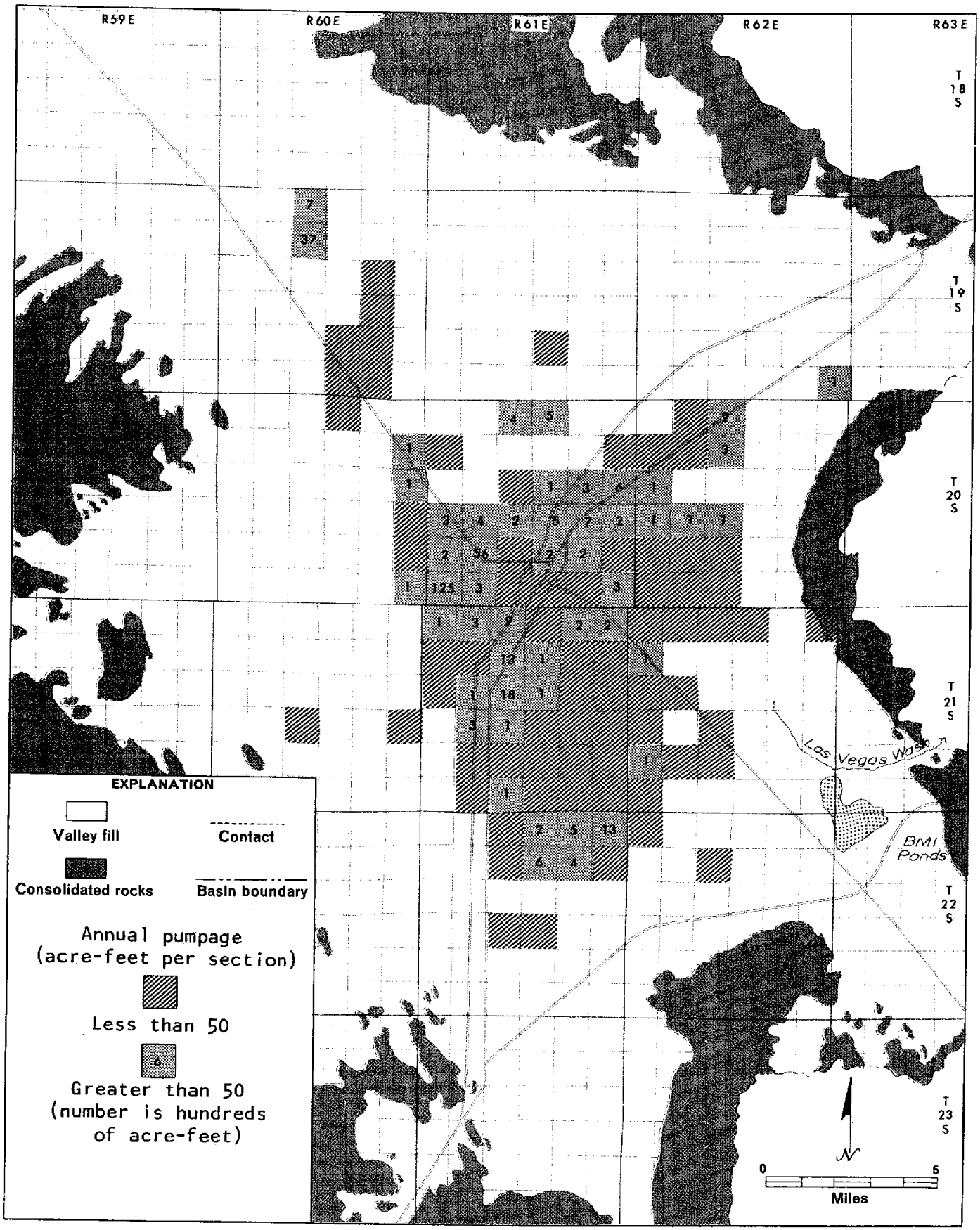


Figure 9.--Distribution of total pumpage in 1955.

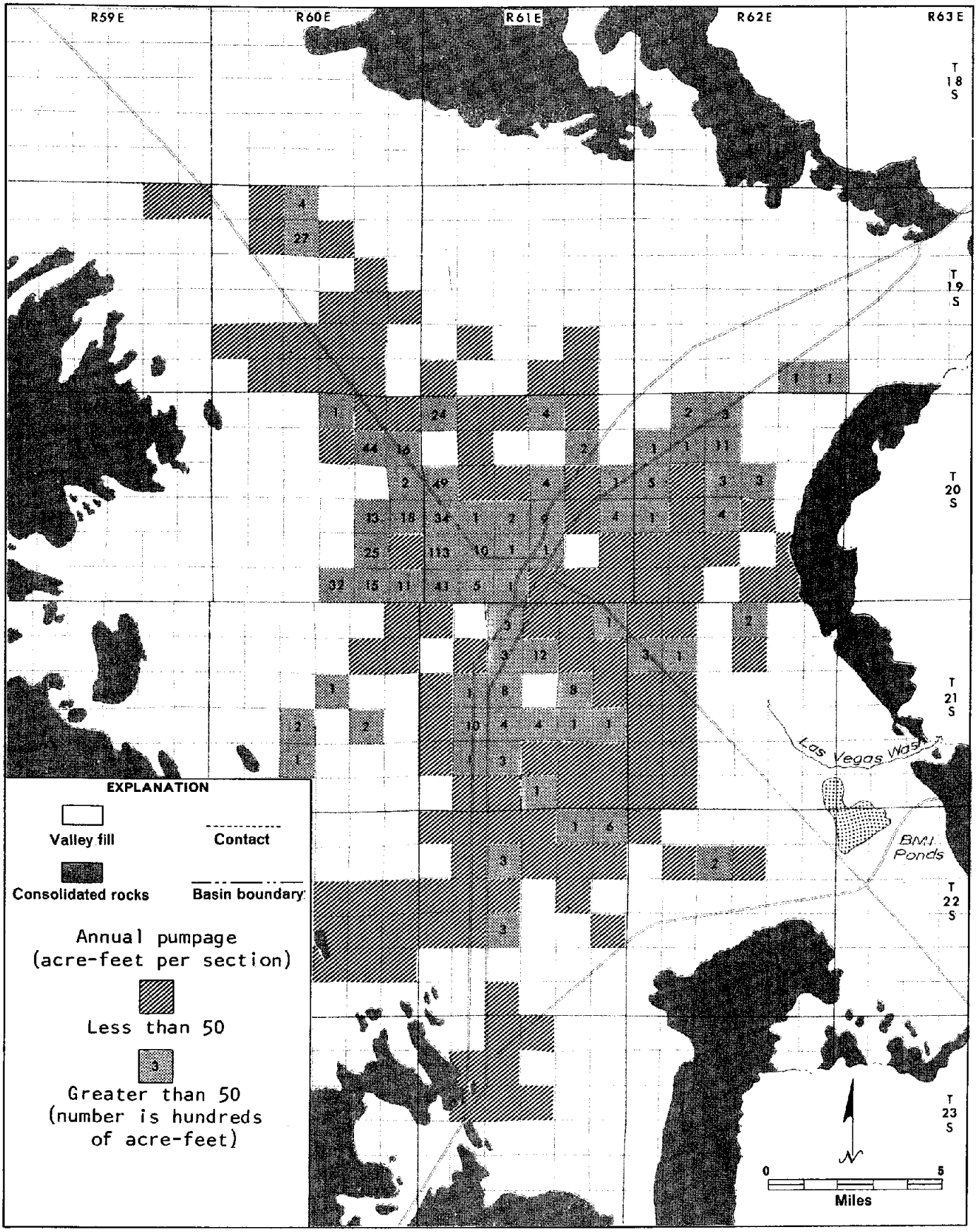


Figure 10.--Distribution of total pumpage in 1973.

area. Here, recharge from imported water and sewage effluent coupled with the absence of local areas of heavy pumpage, have resulted in either no significant change or in some places a slight rise in water levels.

In the near-surface reservoir, areas with a net rise in water levels commonly are associated with secondary recharge from irrigated lawns, irrigated golf courses, irrigated farms, sewage effluent, tail water from BMI evaporation ponds, or seepage from Las Vegas Wash. Clay and silt deposits reduce the hydraulic continuity between the near-surface reservoir and the underlying principal aquifers. In some places, consequently, the water level has risen in the near-surface reservoir while the potentiometric surface has declined in the underlying principal aquifers.

Net Change, February 1955 to February 1973

Figure 11 shows the approximate net change in water levels in the principal aquifers from February 1955 to February 1973. The maximum decline of about 180 feet is offset slightly upgradient from adjacent areas of heavy pumping. This could be due to errors in contouring caused by sparse data in 1955, or it may be associated with a combination of factors such as areal variation in hydraulic properties of the reservoirs and seasonal variations in pumpage. If comparisons had been made during the pumping season rather than in February, the area of maximum change would have coincided with centers of heavy pumping. Figure 12 shows the approximate net change in water levels in the near-surface reservoir during the period February 1955 to February 1973. Contours are shown only for that area where the near-surface reservoir exists as a mappable unit. Within this area, declines typically are much less than in the underlying principal aquifers. The magnitude of decline generally increases toward the west edge of the near-surface reservoir, where it approaches the magnitude of the decline in the principal aquifers. The large area of no decline or a net rise generally is caused by secondary recharge from Lake Mead water and from pumped ground water.

Net Change, February 1963 to February 1973

Figure 13 shows the approximate net change in water levels in the principal aquifers during the 10-year period 1963-73. The maximum decline of slightly more than 100 feet corresponds roughly with the center of maximum pumpage. This suggests that the offset between areas of heavy pumping and maximum water-level declines shown in figure 11 may be due in part to inadequate data. Figure 14 shows the approximate net change in water levels in the near-surface reservoir during the period February 1963 to February 1973.

Net Change, Natural Conditions to February 1973

Approximate net changes in potentiometric surface in the principal aquifers between near-natural conditions in 1912 and February 1973 provide some information about cumulative effects of development on the natural system, and give perspective to the magnitudes of change that

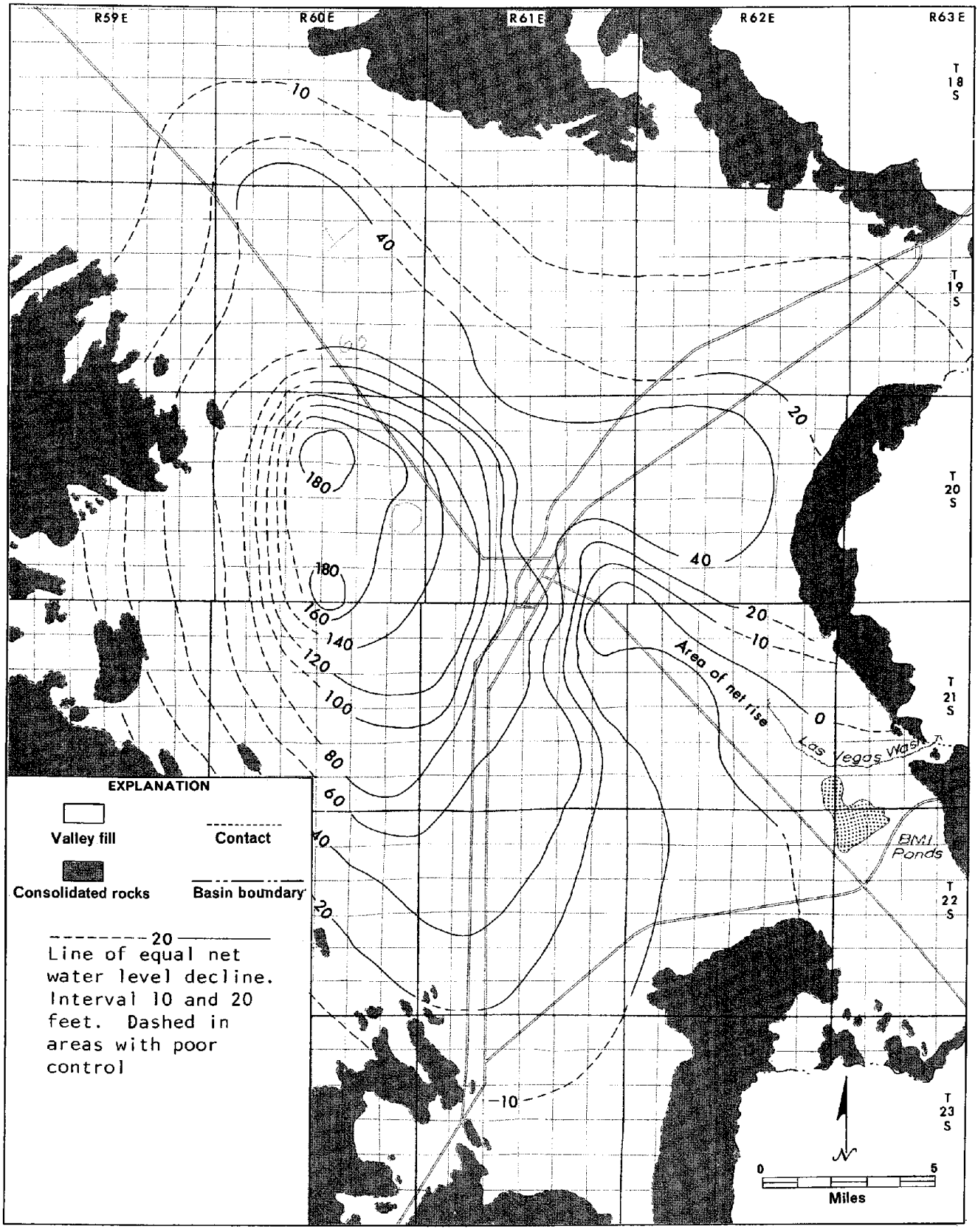


Figure 11.--Net change in water levels, principal aquifers, February 1955-February 1973.

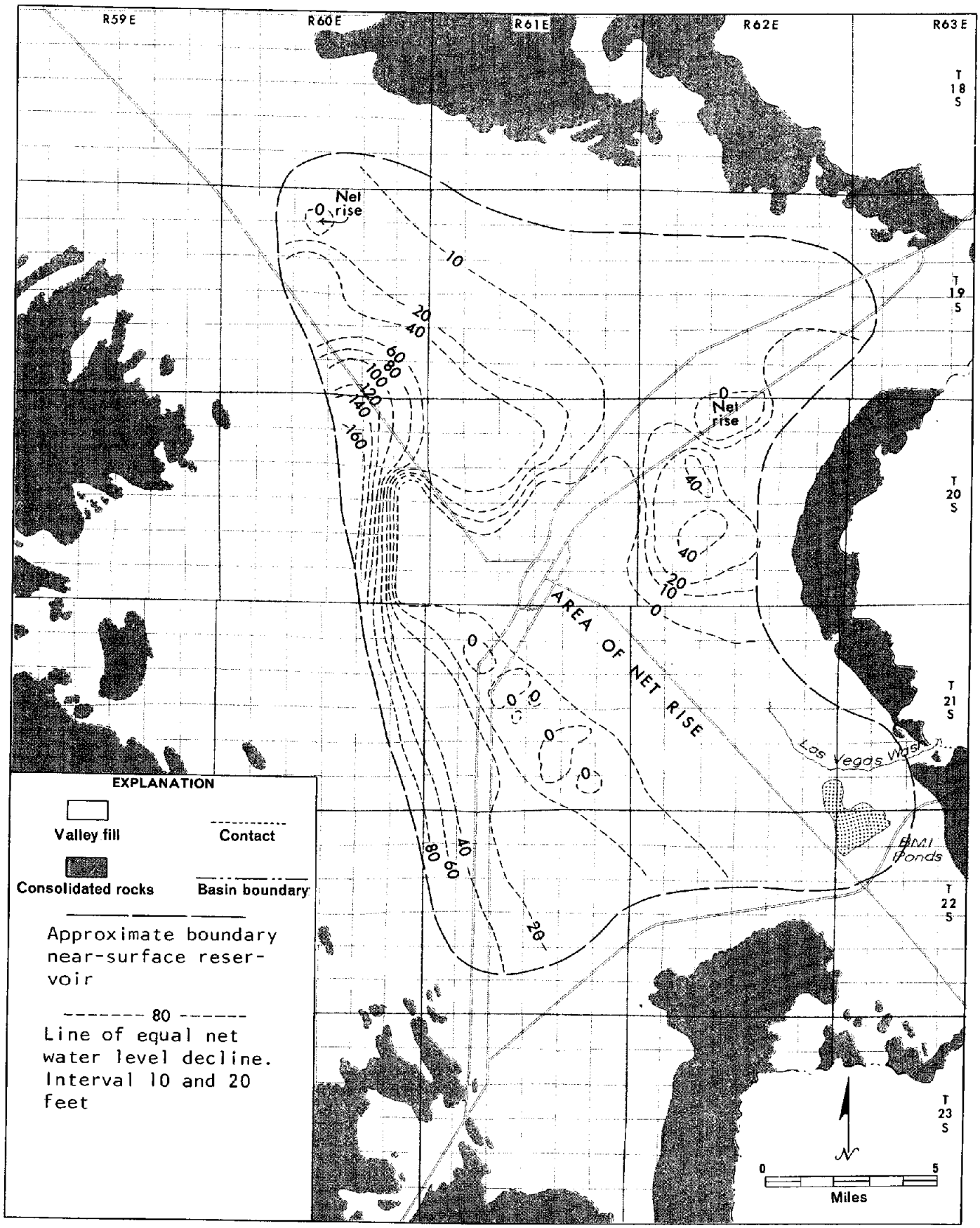


Figure 12.--Net change in water levels, near surface reservoir, February 1955-February 1973.

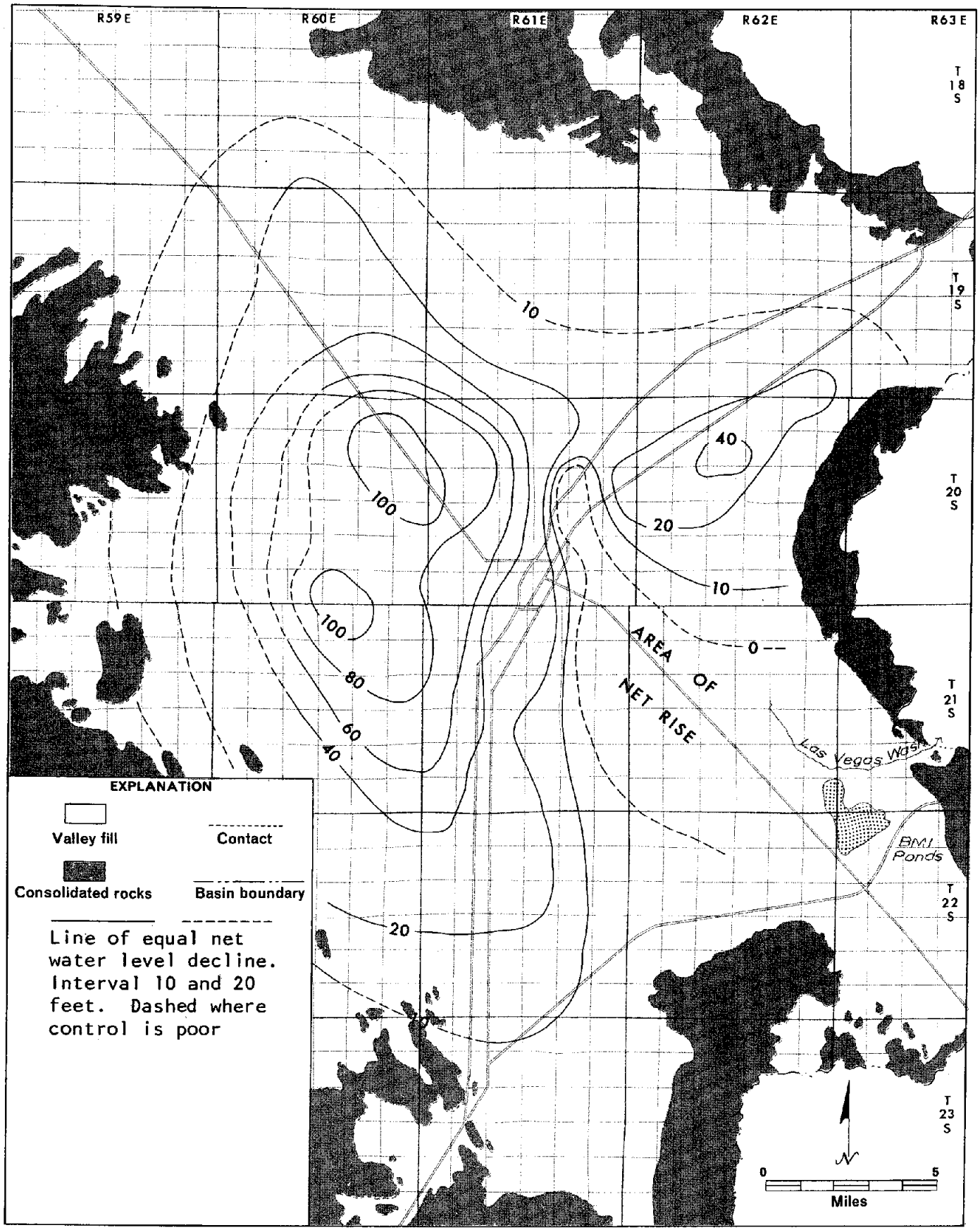


Figure 13.--Net change in water levels, principal aquifers, February 1963-February 1973.

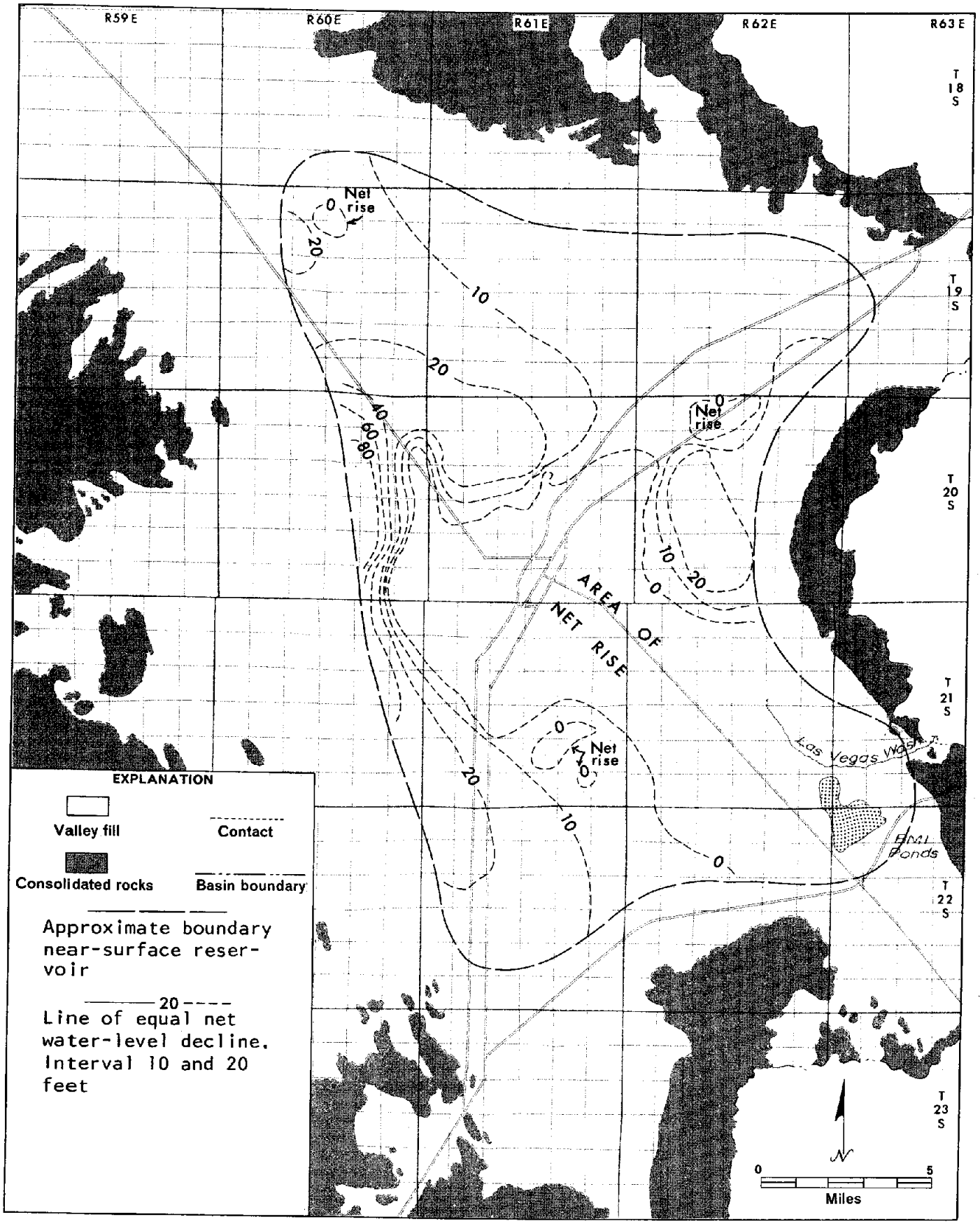


Figure 14.--Net change in water levels, near surface reservoir, February 1963-February 1973.

occurred during the period covered by this report. Figure 15 shows the approximate net change in water levels in the principal aquifers from natural conditions through February 1973. This map was constructed as the approximate sum of changes shown by Domenico and others (1964, fig. 24; period 1912-44), Malmberg (1965, pl. 6; period 1944-56), and figure 12 of this report. The maximum decline of slightly more than 240 feet occurred near the area of heavy pumping in the northwest part of the valley.

Annual Changes, February 1971 to March 1975

The Southern Nevada Water Project became operational in June 1971; however, 1972 was the first complete year of full scale operation. Annual ground-water pumpage decreased from about 85,000 acre-feet in 1971 to about 70,000 acre-feet in 1972. Capacity of the first phase of the project was sufficient to meet demands for additional water through 1973, and ground-water pumpage remained at about 70,000 acre-feet in that year. By 1974, storage and distribution facilities for imported water were operating at near capacity. Consequently, demands for additional water were met by pumping ground water, and pumpage increased to about 78,000 acre-feet in that year.

The response of the principal aquifers to these changes in pumping rates is summarized by a series of four maps. The approximate annual net water-level changes in wells that occurred during the period February 1971 to February 1972, February 1972 to February 1973, February 1973 to March 1974, and March 1974 to March 1975 are shown in figure 16-19, respectively. The general pattern shown by these maps is declining water levels through 1971, a pronounced recovery during the period February 1972 to February 1973, and the declining water levels since. The rate of decline accelerated during the period March 1974 to March 1975 as a result of increased pumpage. However, the declines in excess of 15 feet shown in figure 19 may be due in part to a variation in the seasonal distribution of pumping.

Storage Depletion

Period 1955-72

Depletion of ground-water storage associated with declining water levels can be estimated as the product of the average amount of decline, the area of decline, and the specific yield or storage coefficient of the sedimentary deposits involved.

This general method was used to compute estimates of storage depletion from the principal aquifers for the periods 1955-72 and 1963-72 (tables 4 and 5). Amounts and areas of decline were determined from figures 11 and 13. Storage coefficients for the respective areas of decline were determined from figure 7.

Storage depletion in the near-surface reservoir could not be estimated with a great degree of accuracy. Water occurs under both confined and unconfined conditions, and heads may vary significantly with well depth.

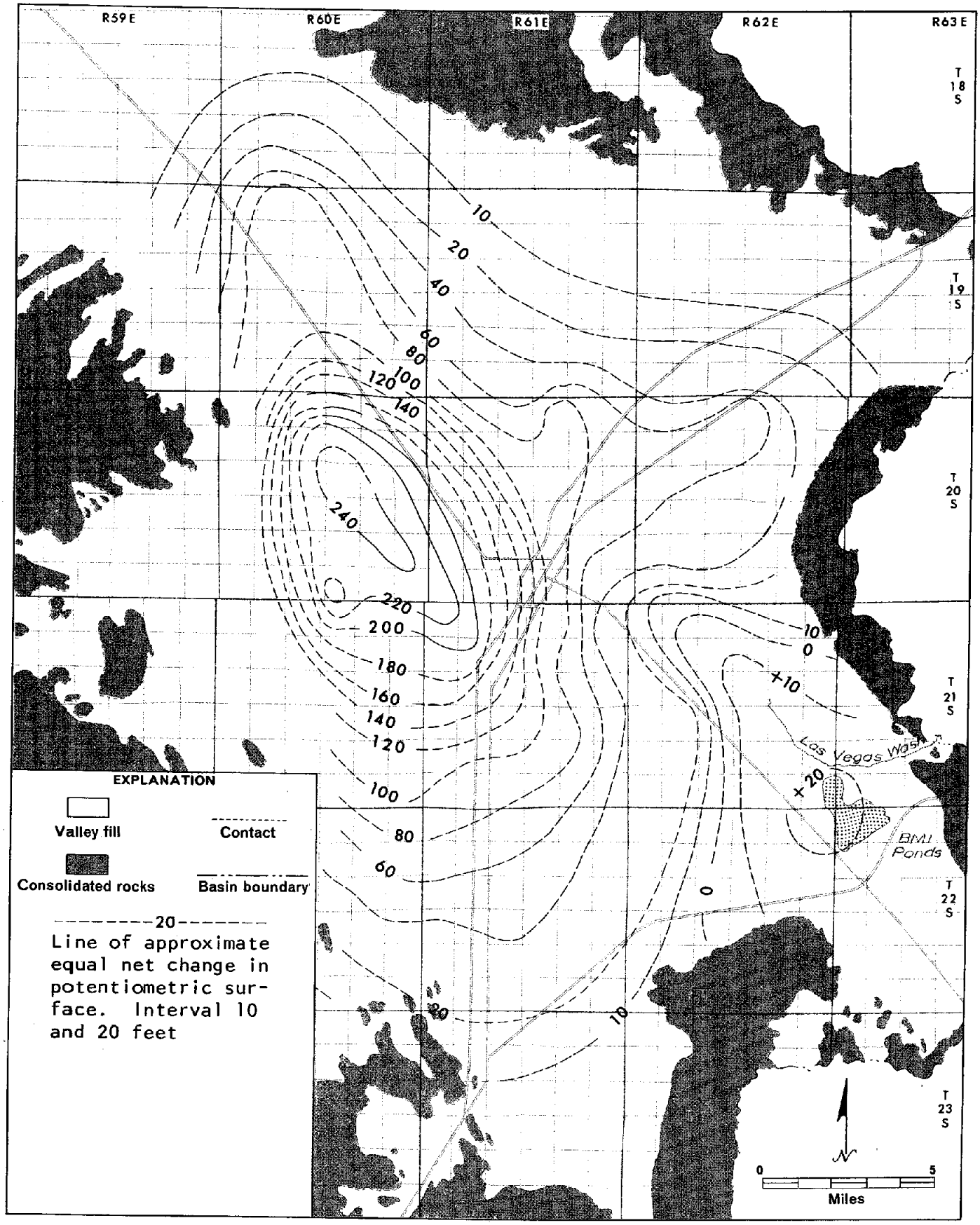


Figure 15.--Approximate net change in potentiometric surface, principal aquifers, natural conditions to February 1973.

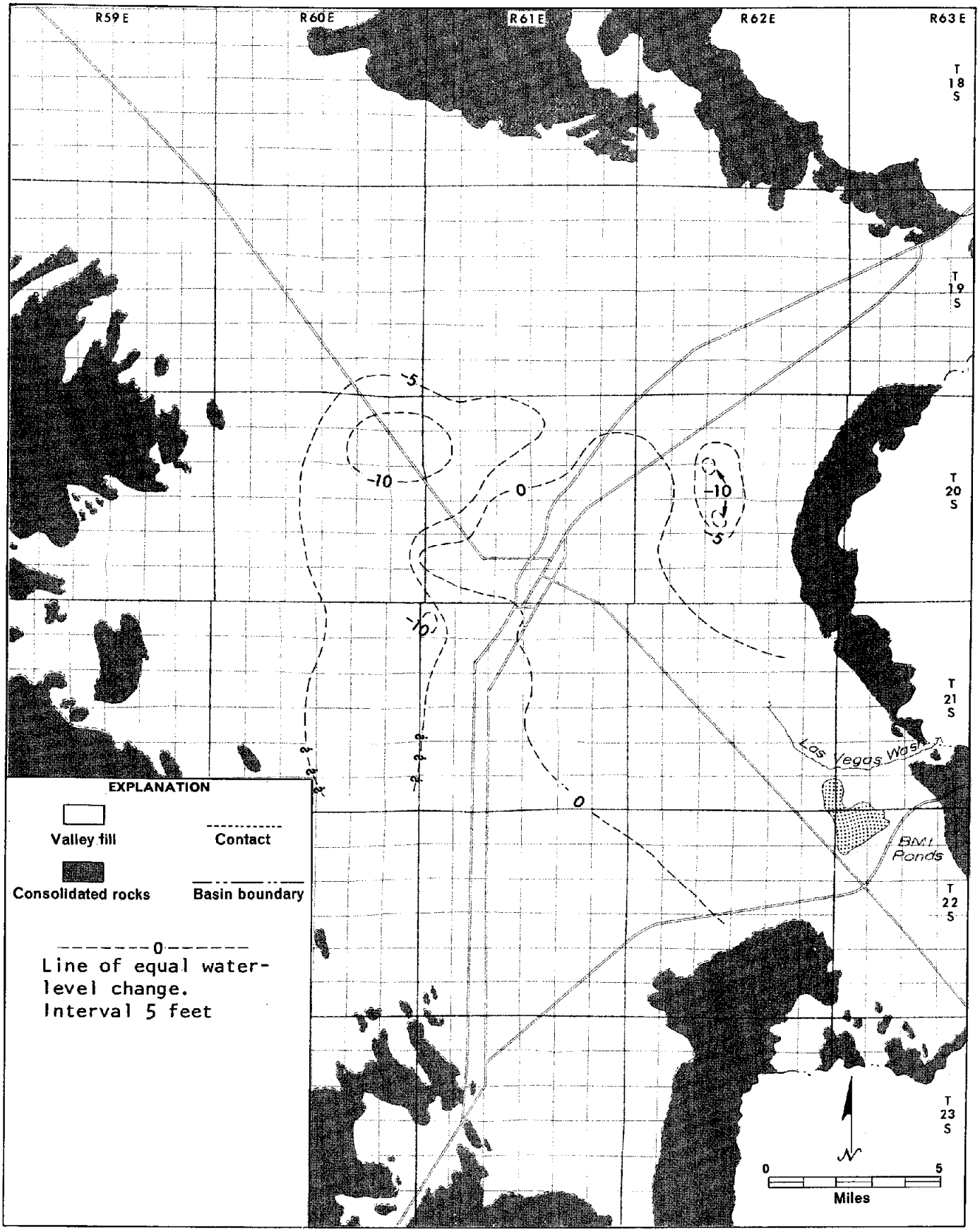


Figure 16.--Approximate net change in water levels in wells that penetrate the principal aquifers, February 1971-February 1972.

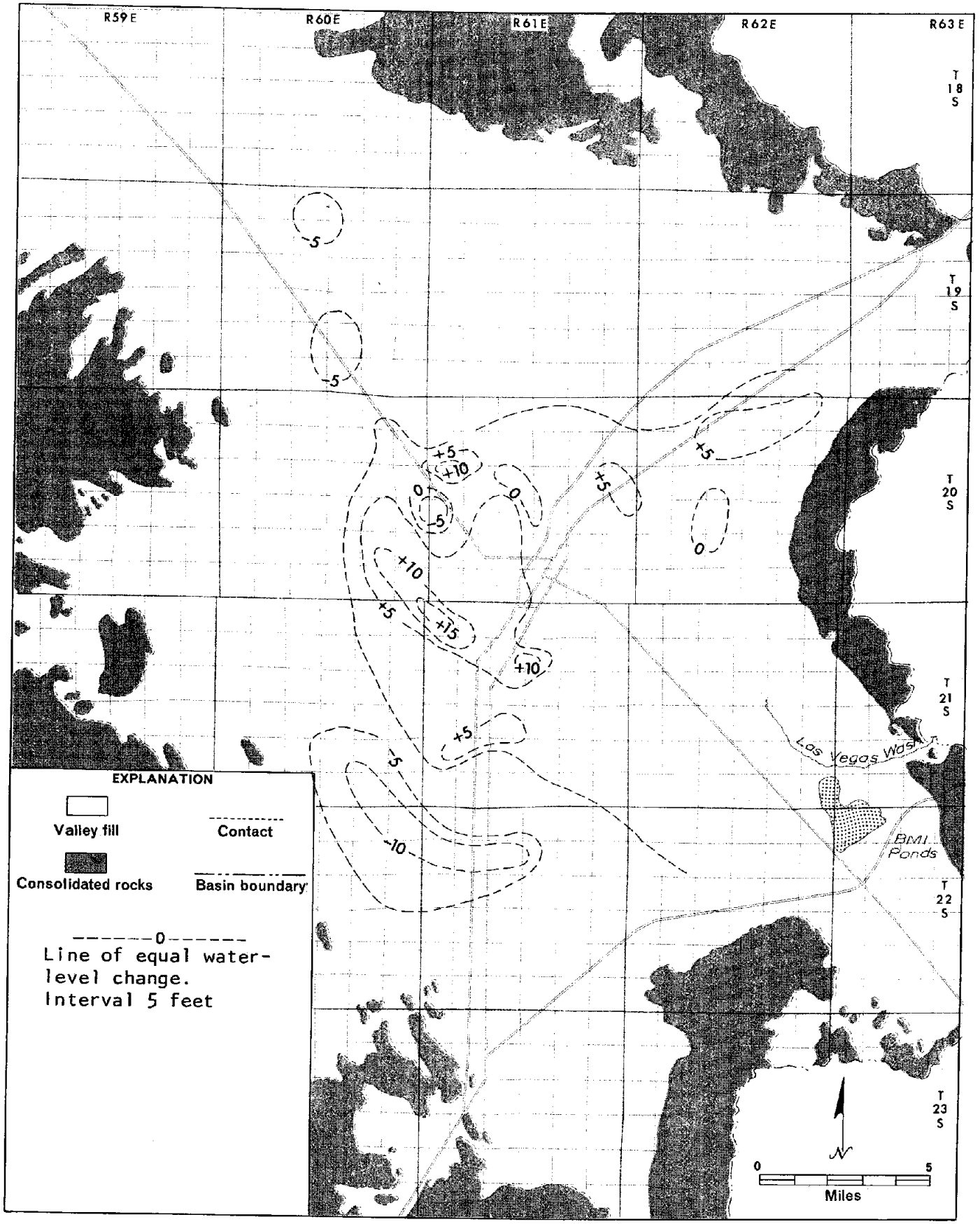


Figure 17.--Approximate net change in water levels in wells that penetrate the principal aquifers, February 1972-February 1973.

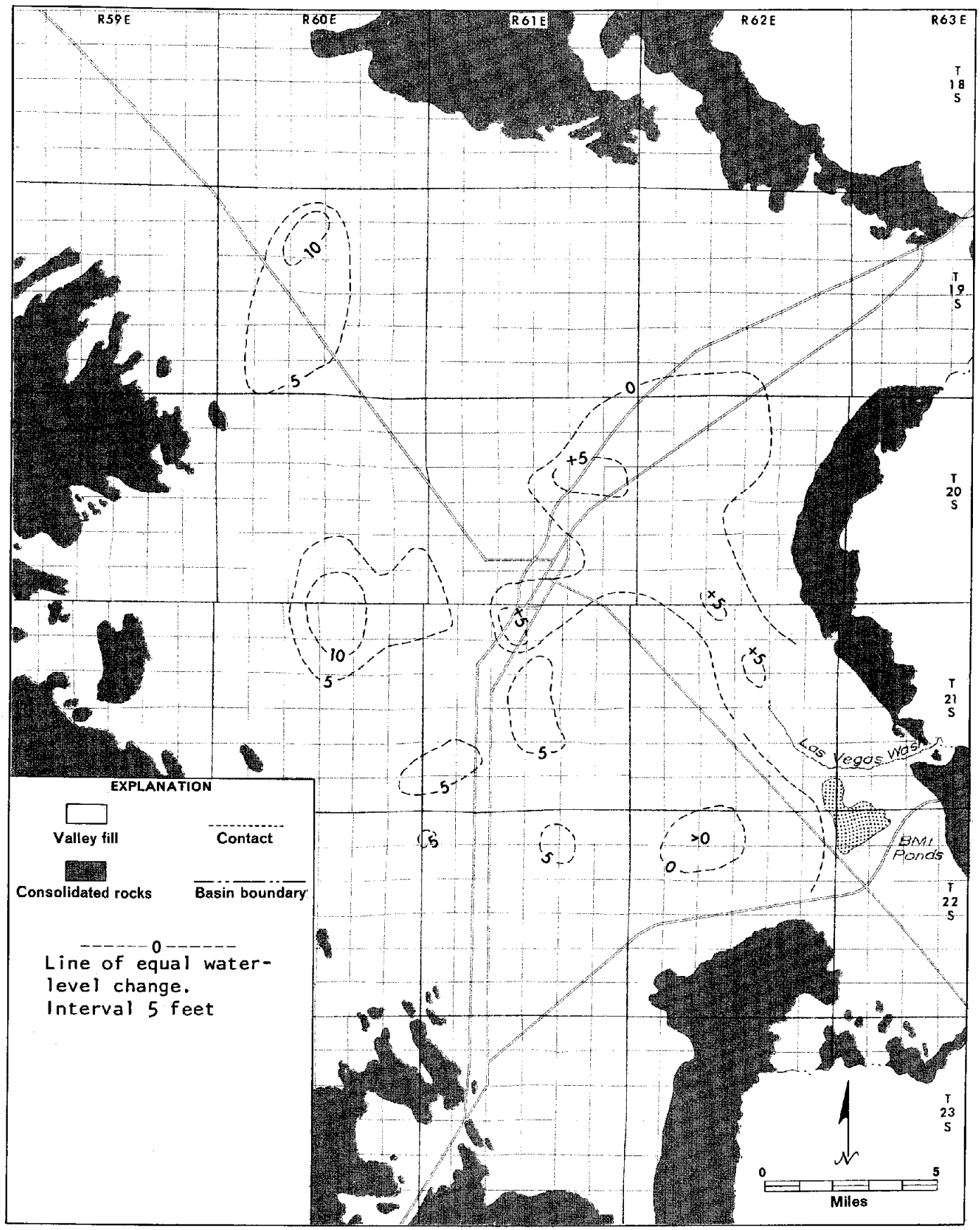


Figure 18.--Approximate net change in water levels in wells that penetrate the principal aquifers, February 1973-March 1974.

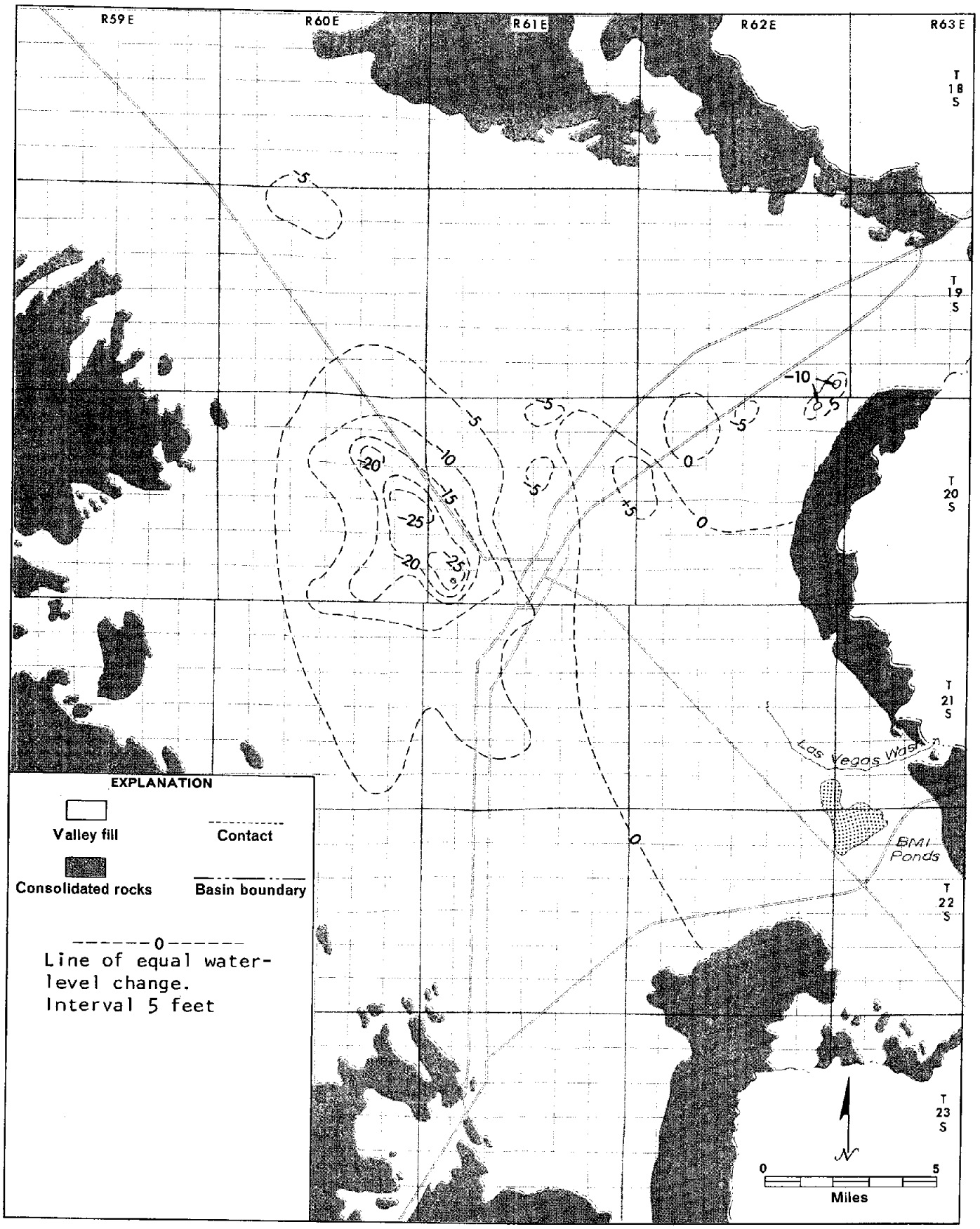


Figure 19.--Approximate net change in water levels in wells that penetrate the principal aquifers, March 1974-March 1975.

Detailed information on the distribution of specific yield within the near-surface reservoir is not available; however, the generally fine-grained nature of the materials suggests that the specific yield would be between 5 and 10 percent. Delayed drainage is common in these deposits, and some water-level changes measured in wells may represent changes under partly confined conditions; consequently, a storage coefficient of 0.05 is used to compute the estimates derived in this report. Areas and amounts of water-level change were determined from figures 12 and 14. Table 6 summarizes computations of estimated storage depletion from the near-surface reservoir.

The several estimates of storage depletion from the valley-fill reservoir are summarized in table 7. No direct estimates of storage depletion from consolidated rocks were made, however significant depletion may be occurring in the consolidated rocks which surround the valley-fill reservoir. Some crude estimates of the magnitude of depletion from consolidated rocks are developed in a later part of this report. Estimates for the subperiod 1955-62 were determined by difference.

Total Storage Depletion, Natural Conditions to 1972

By the end of 1972, about 2.1 million acre-feet (MAF) of ground water had been pumped from the valley-fill reservoir since development began. Water-level declines associated with this pumpage have been shown in figure 15. Cumulative storage depletion as of 1955, estimated from data developed by Malmberg (1965, fig. 15), was about 670,000 acre-feet. When added to the estimated 600,000 acre-feet of depletion during the period 1955-72 (table 7), this results in an estimated total storage depletion of about 1.3 MAF. Thus, about 64 percent of the total pumpage has been derived from storage.

Land Subsidence

Subsidence in Las Vegas Valley is due to three principal causes: (1) Regional subsidence and widespread tilting of the entire Lake Mead Reservoir and adjacent areas to the south, resulting from tectonic activity; (2) subsidence of a broad basin-like depression centering in Boulder Canyon (about 12 miles upstream from Hoover Dam) resulting from the additional load imposed on the earth's surface by the impoundment of the Colorado River behind Hoover Dam; and (3) local subsidence in Las Vegas Valley due to decline of artesian pressure and resulting compaction of the unconsolidated alluvial fill (Malmberg, 1964, p. 4). This last type of subsidence is the only one evaluated in this report.

Land subsidence caused by pumping occurs when a drop in hydraulic head causes water to be squeezed out of fine-grained deposits due to a reduction in pore pressure. The removal of water from the deposits causes vertical settling and compaction, and the volume of water removed equals the volume of compaction. Ground-water pumpage in Las Vegas Valley has resulted in significant land subsidence in parts of the valley. This phenomenon has been studied by several investigators, including Malmberg (1964), Domenico and others (1964), and Mindling (1971). These reports describe the subsi-

Table 4.--*Estimated storage depletion in principal aquifers, 1955-72*

Nature of reservoir and storage coefficient (S)	Water-level decline 1/ (feet)	Area (acres) (1)	Average net decline (feet) (2)	Depletion 1,2/ (acre-feet) (3)
Artesian (leaky) S=0.001	Net rise	17,000	+5(±)	+85
	0-10	22,000	5	110
	10-20	33,000	15	500
	20-40	23,000	30	690
	40-60	44,000	50	2,200
	60-80	8,600	70	600
	80-100	4,900	90	440
	100-120	4,900	110	540
	120-140	6,200	130	810
	140-160	5,600	150	840
	160-180	2,900	170	490
	>180	220	190	40
		Net subtotal (rounded)		7,200
Transitional S=0.01	10-20	930	15	140
	20-40	3,100	30	930
	40-60	5,200	50	2,600
	60-80	2,600	70	1,800
	80-100	2,200	90	2,000
	100-120	1,300	110	1,400
	120-140	1,500	130	2,000
	140-160	1,000	150	1,500
	160-180	2,500	170	4,200
	>180	1,700	190	3,200
Transitional S=0.04	40-60	560	50	1,100
	60-80	240	70	670
	80-100	1,100	90	4,000
	100-120	930	110	4,100
	120-140	1,200	130	6,200
	140-160	1,300	150	7,800
	160-180	1,800	170	12,000
	>180	50	190	380
		Subtotal (rounded)		56,000
Water table (considering delayed drainage) S=0.13	Net rise	8,600	+5(±)	+5,600
	0-10	54,000	5	35,000
	10-20	38,000	15	74,000
	20-40	21,000	30	82,000
	40-60	13,000	50	84,000
	60-80	7,400	70	67,000
	80-100	3,700	90	43,000
	100-120	1,400	110	20,000
	120-140	660	130	11,000
		Net subtotal (rounded)		410,000
Total (rounded)				470,000

1. Except where "net rise" or "+" is indicated.
2. Column (3) is product of columns (1) and (2) and storage coefficient (S).

Table 5.--*Estimated storage depletion in principal aquifers, 1963-72*

Nature of reservoir and storage coefficient (S)	Water-level decline 1/ (feet)	Area (acres) (1)	Average net decline (feet) (2)	Depletion 1,2/ (acre-feet) (3)
Artesian (leaky) S=0.001	Net rise	36,000	+5(±)	+180
	0-10	30,000	5	150
	10-20	38,000	15	570
	20-40	35,000	30	1,000
	40-60	9,300	50	460
	60-80	8,500	70	600
	80-100	10,000	90	900
	>100	4,000	110	440
		Net subtotal (rounded)		3,900
Transitional S=0.01	10-20	2,600	15	390
	20-40	4,200	30	1,300
	40-60	2,200	50	1,100
	60-80	2,300	70	1,600
	80-100	4,900	90	4,400
	>100	1,400	110	1,500
Transitional S=0.04	10-20	150	15	90
	20-40	1,100	30	1,300
	40-60	1,200	50	2,400
	60-80	4,200	70	12,000
	80-100	930	90	3,300
	>100	170	110	750
		Subtotal (rounded)		30,000
Water table (delayed drainage) S=0.13	Net rise	10,000	+5(±)	+6,500
	0-10	77,000	5	50,000
	10-20	30,000	15	58,000
	20-40	24,000	30	94,000
	40-60	6,300	50	41,000
	60-80	620	70	5,600
		Net subtotal (rounded)		240,000
Total (rounded)				270,000

1. Except where "net rise" or "+" is indicated.
2. Column (3) is product of columns (1) and (2) and storage coefficient (S).

Table 6.--*Estimated storage depletion in the near-surface reservoir, 1955-72 and 1963-72*

Water-level decline 1/ (feet)	Average net decline (feet) (1)	Period 1955-72 Area (acres) (2)	Period 1955-72 Depletion 1,2/ (acre-feet) (3)	Period 1963-72 Area (acres) (2)	Period 1963-72 Depletion 1,2/ (acre-feet) (3)
0 to +20±	a +5,+7	56,000	+20,000	62,000	+16,000
0-10	5	45,000	11,000	49,000	12,000
10-20	15	33,000	25,000	39,000	29,000
20-40	30	18,000	27,000	21,000	32,000
40-60	50	16,000	40,000	920	2,300
60-80	70	3,000	10,000	1,100	3,800
80-100	90	2,400	11,000	1,800	8,100
100-120	110	1,400	7,700	--	--
120-140	130	830	5,400	--	--
140-160	150	810	6,100	--	--
160-180	170	1,100	9,400	--	--
Totals (rounded)		178,000	130,000	175,000	71,000

1. Except where "+" is indicated.
2. Column (3) is product of columns (1) and (2) and storage coefficient (S) which equals 0.05.

a. Average rise for period 1955-72 is 7 feet; average rise for period 1963-72 is 5 feet.

Table 7.--*Summary of storage depletion estimates*

Source	1955-62 1/	1963-72	1955-72
Principal aquifers	200,000	270,000	470,000
Near-surface reservoir	59,000	71,000	130,000
Totals (rounded) 2/	260,000	340,000	600,000

1. Determined by difference: depletion for 1955-72 minus depletion for 1963-72.
2. Do not include estimates for consolidated rocks.

dence to 1963, when the last round of instrumental leveling was completed. In November 1972, the Nevada Highway Department releveled some of the bench marks in the subsidence network and computed relative changes based on the assumption that altitudes of bench marks X366 and T368 had not changed since 1963. Errors due to regional tilting and possibly some minor subsidence near bench mark X366 are included in the above assumption; however, the results are considered adequate for the purposes of this study.

Figure 20 shows approximate contours of equal land subsidence presumably due to pumping during the period 1963-72, based on the Nevada Highway Department data. The maximum observed subsidence of about 2 feet was in the northeast part of T. 20 S., R. 60 E., about a mile east of the Tonopah Highway (U.S. 95). Subsidence of nearly 2 feet was also observed in T. 21 S., R. 61 E., slightly west of The Strip between Desert Inn and Flamingo Roads. Subsidence in both areas is near heavy pumping (fig. 10). A more detailed evaluation of either area might indicate subsidence greater than that observed from the existing network data points. The volume of compaction during this approximate 10-year period was about 40,000 acre-feet. This was equal to about 5 percent of the total pumpage. Mindling (1971, table 3) reported the volume of compaction during the period 1957-63 to be 27,650 acre-feet. Thus, assuming the volume of compaction during the period 1955-63 to be about 28,000 acre-feet, the total volume of compaction during the period 1955-73 was about 68,000 acre-feet.

Evaluation of the vertical distribution of compaction is beyond the scope of this study. However, some information developed by previous workers is pertinent. Mindling (1971, p. 12-18) described data collected from compaction recorders in the NE¼ sec. 23, T. 20 S., R. 60 E. Data from 1965 showed that most compaction that year was in the interval between 0 and 200 feet. Compressibility of fine-grained sediments was greatest near the surface, and generally decreased with depth. Thus, if appreciable head declines occur in the near-surface reservoir, significant compaction may occur. More commonly, maximum head changes occur adjacent to perforated intervals of pumped deep wells. Domenico and Maxey (1964, p. 8) used measurements of relative casing protrusion of adjacent deep and shallow wells, resulting from subsidence, to estimate the probable interval where compaction had occurred. Observations made in the Nellis Air Base well field on Craig Road (sec. 3, T. 20 S., R. 61 E.) suggested that most compaction there probably occurred between 300 and 425 feet. Observations made on the SE¼ sec. 22, T. 20 S., R. 60 E., suggested that compaction there most probably had occurred between 200 and 600 feet.

Changes in Ground-Water Regimen

Spring Discharge

Malmberg (1965, table 9) reported that spring discharge in Las Vegas Valley decreased from about 6,400 acre-feet per year in 1906 to about 1,400 acre-feet per year in 1955. As water levels declined during the period 1955-73, discharge from the major springs in the vicinity of Las

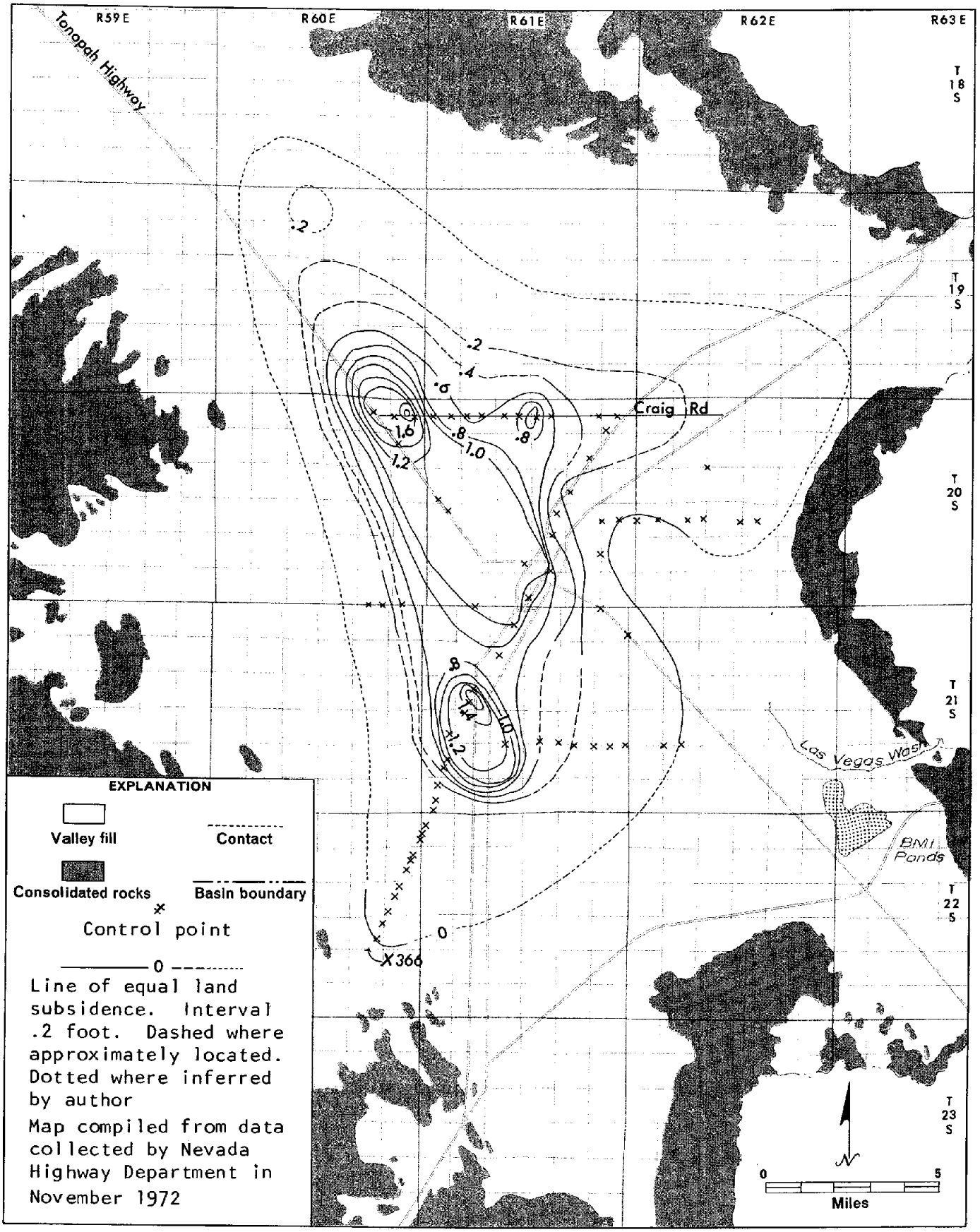


Figure 20.--Approximate land subsidence, 1963-72.

Vegas ceased. As of 1975, none of the major springs in the vicinity of Las Vegas flowed, however, some small springs along fault scarps in T. 21 S., R. 62 E. in the lower parts of the valley flowed as well as some springs and seeps along parts of Las Vegas Wash which probably were supplied by secondary recharge. The total reduction in spring discharge during the period February 1955 to February 1973, relative to natural conditions, was on the order of 110,000 acre-feet. This water presumably was captured by pumping.

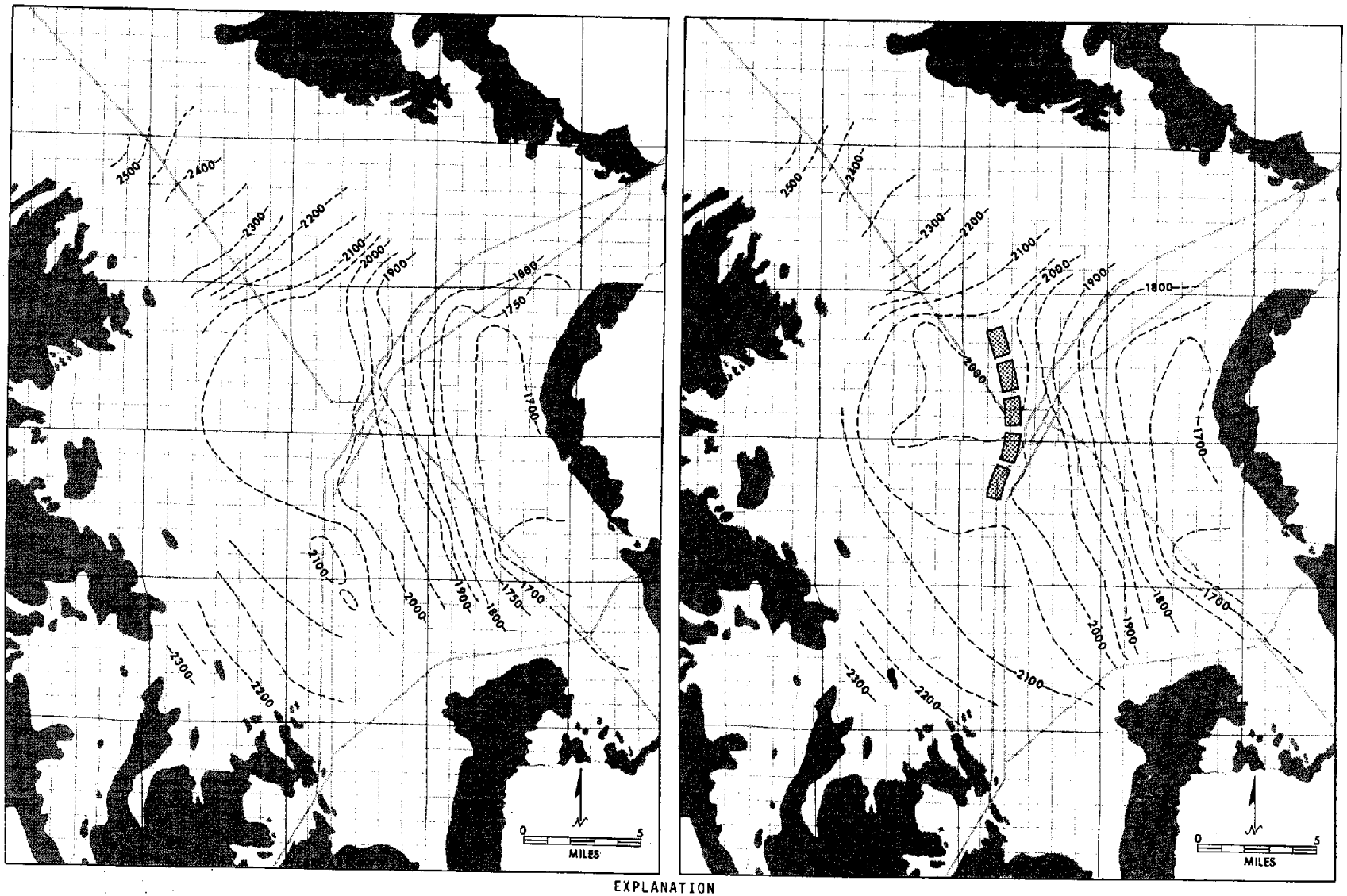
Gradient Reversals

Vertical gradients.--Under natural conditions, the potentiometric surface in the principal aquifers was above the water table in the near-surface reservoir throughout most of the central part of the valley. This resulted in upward leakage, which was the means by which most ground water was discharged from the principal aquifers. By 1975, the potentiometric surface had declined below the water table throughout much of the valley. This resulted either in (1) the removal of water from storage in the overlying near-surface reservoir or (2) the recycling of some water back into the principal aquifers in areas of secondary recharge. This condition is evaluated in more detail in a later part of this report.

Development of ground-water divides.--Figure 11 shows that ground-water declines are concentrated in T. 20 S., R. 60 E., near areas of heavy pumping. Under natural conditions, ground water moved through this area in an easterly direction. Water-level declines have caused this gradient to reverse each year for many years, as heavy summer pumping dropped water levels enough to cause a depression in the area of pumping. This resulted in a temporary reversal of flow gradients toward the pumping wells. Water levels generally recovered during winter months, and reversed gradients were maintained only in the immediate vicinity of pumping wells. However, by March 1975, increased pumping and continued water-level declines resulted in the development of a year-round depression in the main areas of pumping. In 1975, a ground-water divide was located just east of the main well field of the Las Vegas Valley Water District. These changes are illustrated in figure 21, which shows approximately located contours of the potentiometric surface in February 1973, after the first full year of operation of the Southern Nevada Water Project, and in March 1975.

Secondary Recharge Areas

High-density home tracts are areas of significant secondary recharge because of the infiltration of water used to irrigate lawns. Golf courses, parks, irrigated farms, parts of Las Vegas Wash downstream from sewage treatment plants, and the BMI tailings ponds near Henderson are other secondary recharge areas. (Intensive efforts by BMI are currently underway to prevent infiltration from these ponds.) This water recharges the near-surface reservoir. Effects of this recharge are shown in figures 11 and 13, where the water table has stabilized or risen. The amount of water in these areas that is actually moving downward to recharge the principal aquifers depends on the hydraulic gradient between the water table and the principal aquifers and the vertical hydraulic conductivity of deposits in the near-



EXPLANATION

Valley-fill

Consolidated rocks

Contact

Basin boundary

----------2000---------
Water-level contour, shows altitude of water levels in wells that penetrate the principal aquifers. Dashed because approximately located. Contour interval 50 feet. Datum is mean sea level

Ground-water divide

Figure 21.--Water level contour maps for wells that penetrate the principal aquifers, February 1973 and March 1975.

surface reservoir. In much of the valley, most secondary recharge circulates only to shallow depth and the amount that actually reaches the principal aquifers probably is small. However, secondary recharge to the principal aquifers may be significant along the flanks of the alluvial fans that border the valley. This now occurs in parts of T. 20 S., R. 60 E., and may be expected to occur in parts of T. 21 S., R. 60 E., where municipal water supplies have recently been made available. Additional secondary recharge may occur near Henderson, where new housing developments will be supplied by imported water. Some secondary recharge to deep aquifers was apparently occurring near Henderson as of 1975, as water levels in well S22/63-4ddb1 (750 ft deep and not perforated above 400 ft) rose at an average rate of nearly 0.7 foot per year during the period March 1971 to March 1975.

Changes in Hydraulic Conductivity of Confining Layers

When ground-water withdrawal results in compaction of fine-grained deposits, land subsidence is the most apparent consequence. However, because this compaction is largely irreversible, a permanent decrease in the hydraulic conductivity of these materials also results. In Las Vegas Valley, one consequence of this may be a reduction in the hydraulic continuity between the near-surface reservoir and the principal aquifers. Currently the change in hydraulic conductivity may be small, however, it is beyond the scope of this study to attempt any quantitative determination. Eventually this process may have a significant effect on the long-term response to pumping and it should be evaluated in future studies.

Changes in Phreatophyte Densities

Pumping from deep aquifers in an alluvial basin will eventually lower the water table in areas of natural discharge. Evapotranspiration losses from phreatophytes and bare soil will be curtailed, and that water will be captured by pumping. Throughout much of Las Vegas Valley, however, secondary recharge from both pumped water and imported water has either equaled or exceeded any downward leakage to the principal aquifers. Consequently, with the exception of areas cleared for development, phreatophyte stands in the lower part of the valley are as vigorous as, or more vigorous than, under natural conditions. Therefore, changes in the density and distribution of phreatophytes are generally not reliable indicators of changes in the principal aquifers. Only in parts of T. 19 S., Rs. 60 and 61 E., and T. 20 S., R. 60 E., do phreatophytes clearly show signs of distress. In these areas, mesquite stands commonly exhibit numerous dead branches representative of former vigorous growth. The surviving plants occur as shoots several feet tall growing among clumps of dead branches 6 to 10 feet tall.

Transition from Artesian to Water-Table Conditions

Prior to the beginning of pumping, much of the water in the principal aquifers was under either confined or semiconfined conditions. Confined conditions existed in principal aquifers overlain by well-defined confining beds (fig. 4). Around the margins of the valley, water in deep aquifers is under some artesian head, although unconfined conditions exist at the overlying water table.

Changes in Water Quality

The scope of this study does not include any evaluation of water quality. However, most uses result in some degradation of water quality, and consequently, water involved in secondary recharge may be of poorer quality than the naturally occurring ground water. The degree of degradation expected would be minimal in recharge from heavily watered lawns and golf courses and possibly maximal in recharge from concentrated industrial wastes, such as the tailings ponds at BMI. If significant secondary recharge occurs or is anticipated in a given area, efforts should be made to determine if an undesirable degradation in water quality exists or will develop.

During early stages of development, most of the reservoir probably responded to pumping as an artesian system. In time, however, delayed drainage became significant, and, around the margins of the valley, response to pumping resembled that of a water-table system even though some aquifers at depth remained partly confined. Areas overlain by the near-surface reservoir continued to function as an artesian system overlain by leaky confining beds.

By 1975, head declines in the principal aquifers had progressed to the extent that water levels in localized areas along the western margin of the near-surface reservoir were below the bottom of confining beds. In most places this happens only during seasonal periods of heavy pumping, but in several places along the extreme margin of the near-surface reservoir, declines have been extensive enough to keep water levels beneath the bottom of the near-surface reservoir year-round. This would maximize the vertical gradient, and the principal factor limiting leakage would be the ratio of vertical hydraulic conductivity to thickness of the confining bed. Accelerated water-level declines in corresponding areas of the near-surface reservoir would occur as suggested by declines in figures 12 and 14. Continued head declines will eventually result in more of the principal artesian aquifers being dewatered. Accelerated drainage of the near-surface reservoir may also accelerate subsidence; however, information is insufficient to demonstrate if significant detrimental results are to be anticipated.

SIMULATION OF RESPONSE

Response to pumping during the period 1955-72 was the net result of many interacting hydrologic factors. Most factors varied with location, and some also varied with time. Any evaluation which does not take these variations into account probably would be too oversimplified to be useful. Consequently, a mathematical model capable of treating a multitude of variables which vary in both time and space was used in this study.

The model used was developed by P. C. Trescott and G. F. Pinder of the U.S. Geological Survey (written commun., 1974). It is a finite-difference aquifer model designed to simulate in two dimensions the response to an imposed stress. The version used in this study allows for a heterogeneous aquifer with irregular boundaries and numerous wells, and it permits leakage from confining beds in which the effects of storage are considered. The particular version used was also modified to enable evaluation of the areal distribution of leakage.

Concept of the Ground-Water System

The ground-water system as described in the preceding sections of this report is essentially a thick alluvial reservoir bounded on its sides and bottom by consolidated rocks. Water-bearing properties of the valley fill vary from place to place. Generally, the most productive deposits are on the west side of the valley; deposits in the central part of the valley are predominantly fine-grained materials and are much less productive. The near-surface reservoir consists of slightly more than 200 feet of fine-grained deposits and the base of this unit forms a fairly well-defined confining layer for the underlying principal aquifers over most of the central part of the valley. Ground water in the near-surface reservoir is both confined and unconfined. Coarser grained deposits around the margins of the near-surface reservoir contain interbedded horizons of caliche or cemented materials that retard vertical movement of water. The principal aquifers are confined in the central part of the valley where leakage occurs through the overlying confining bed. Around the margins of the valley, the principal aquifers respond to pumping like an unconfined aquifer with delayed drainage of water; however, the deeper portion of the aquifers respond like a confined aquifer.

The ground-water reservoir underlying Las Vegas Valley functions as a three-dimensional system. For this study, however, the principal aquifers are evaluated as a two-dimensional system parts of which contain both confined and unconfined water. Where the principal aquifers are confined, leakage occurs from the overlying near-surface reservoir. These conditions approximate the three-dimensional character of the reservoir closely enough to meet the needs of this study.

Description of the Model

The model is a computer program written to solve the finite difference approximation of the differential equation of ground-water flow. The aquifer is represented by the finite-difference network shown in figure 22. A finite-difference equation is written for each node in the network. This results in a series of simultaneous equations which are solved by the iterative alternating-direction implicit (A.D.I.) procedure (Douglas and Rachford, 1956).

Parameter Values Used and Assumptions Made

Assumptions made and parameters used in this model are briefly outlined in the following paragraphs:

The bedrock bordering Las Vegas Valley is treated as a no-flow boundary. Configuration of the bedrock is shown in figure 22. Actually, most consolidated rocks store and transmit some water, and thus do not form a completely impermeable boundary. To crudely recognize this, the storage coefficient at nodes adjacent to boundaries was increased by about 8 percent (the value that gave the best match between observed and computed water-level changes during calibration runs). This puts additional water into the valley-fill reservoir in direct proportion to the head decline adjacent to the boundary. Errors are inherent in this approximation, however, not enough is known about the hydraulic properties of the consolidated rocks to incorporate them into the model.

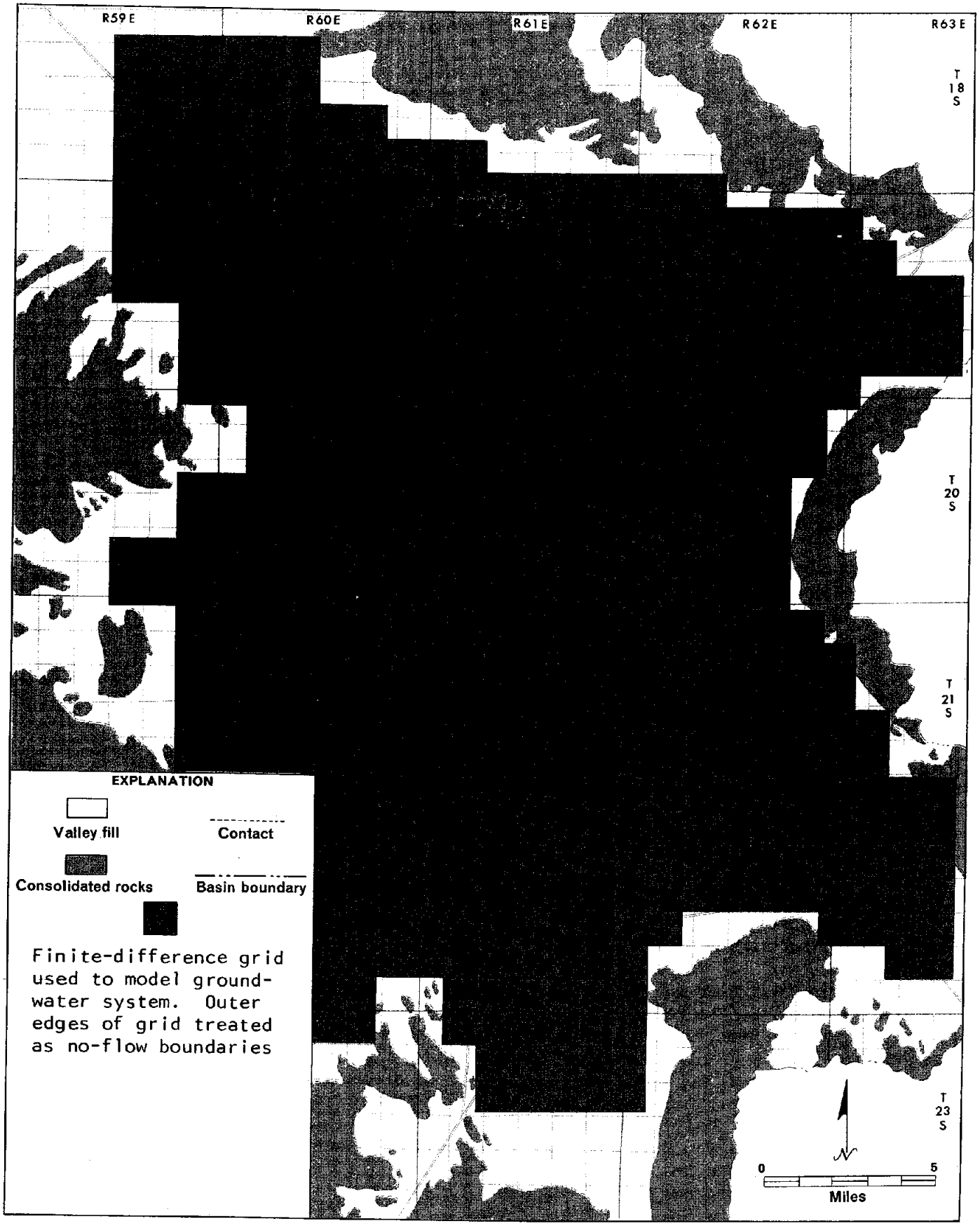


Figure 22.--Finite difference grid used in this study.

Transmissivity distribution used is similar to that shown in figure 6. Transmissivities were assumed to remain constant throughout the simulation period, even though dewatering occurred on the western margin of the area. Because thick accumulations of gravel are present, errors caused by the assumption are probably within the limits of accuracy needed for this study.

The storage coefficients used are those shown in figure 7. Computations made in the area of predominantly unconfined water assume instantaneous release of water from storage. Complete drainage may take many years. Consequently the specific yield of the deposits in this part of the reservoir may ultimately be higher than the storage coefficients used in the model.

Hydraulic conductivity of the confining bed used is that shown in figure 8. The value of specific storage used was 0.001. Vertical hydraulic conductivities of confining beds were assumed to remain constant although in reality some reduction may have occurred in response to compaction. Also, hydraulic head above the confining bed was assumed to remain constant. Errors caused by this assumption probably are small for much of the area of the confining bed where there has been little change in water levels (figs. 12 and 14). However, significant declines have occurred in places along the west margin of the near-surface reservoir, and errors caused by this assumption may be significant. A multilayer analysis of the reservoir will be necessary before more precise evaluations of leakage are possible.

The assumptions made and manner of representing quantities of flow such as recharge and pumpage are discussed for each simulation period.

Method of Analysis

The system and its response to development were simulated in three phases: (1) the natural conditions, (2) the response through 1955, and (3) the period 1955-72. Analysis of the first two phases provided insight about the nature of the system and presented a means of verifying parameter values used in the model. The model was calibrated so that computed heads and water-level changes agreed closely with observed heads and water-level changes by adjusting distributions of transmissivity and recharge during the first phase and the distribution of storage coefficient during the second phase. The third phase represented the period covered by this study. Simulation and analysis of this phase of development provided information about the response to pumping that could not be obtained in any other manner. Data for the period 1963-72 were also developed to permit evaluation of the study period in two segments.

Natural Conditions

Figure 23 shows (A) the approximate potentiometric surface of the principal aquifers under natural conditions and (B) the steady state potentiometric surface generated by the model. The steady state surface was generated using parameters already described, an average annual recharge of about 30,000 acre-feet. The recharge value is of the same general

magnitude as estimates made by previous workers, which range from about 25,000 acre-feet per year (Malmberg, 1965, p. 65) to 35,000 acre-feet per year (Maxey and Jameson, 1948, p. 121). This recharge value is also in agreement with the recharge to the area as estimated by a method developed by Eakin and others (1951), which was computed to be about 30,000 acre-feet per year. Initially, recharge was distributed in the same manner as the estimated precipitation. However, this distribution of recharge did not result in a satisfactory match between observed and computed water levels. To obtain a match between observed and computed water levels, recharge had to be redistributed so that more inflow is contributed by the Spring Mountains and less by the Sheep Range.

In addition to discharge from springs, discharge occurred as upward leakage through confining beds, which then entered the near-surface reservoir and supplied areas of evapotranspiration. Comparison of the distribution of upward leakage with the distribution of phreatophytes under natural conditions provided an additional check on the ability of the model to simulate the natural system. Plate 1 shows the approximate distribution of phreatophytes under natural conditions and the distribution of discharge in the steady-state simulation.

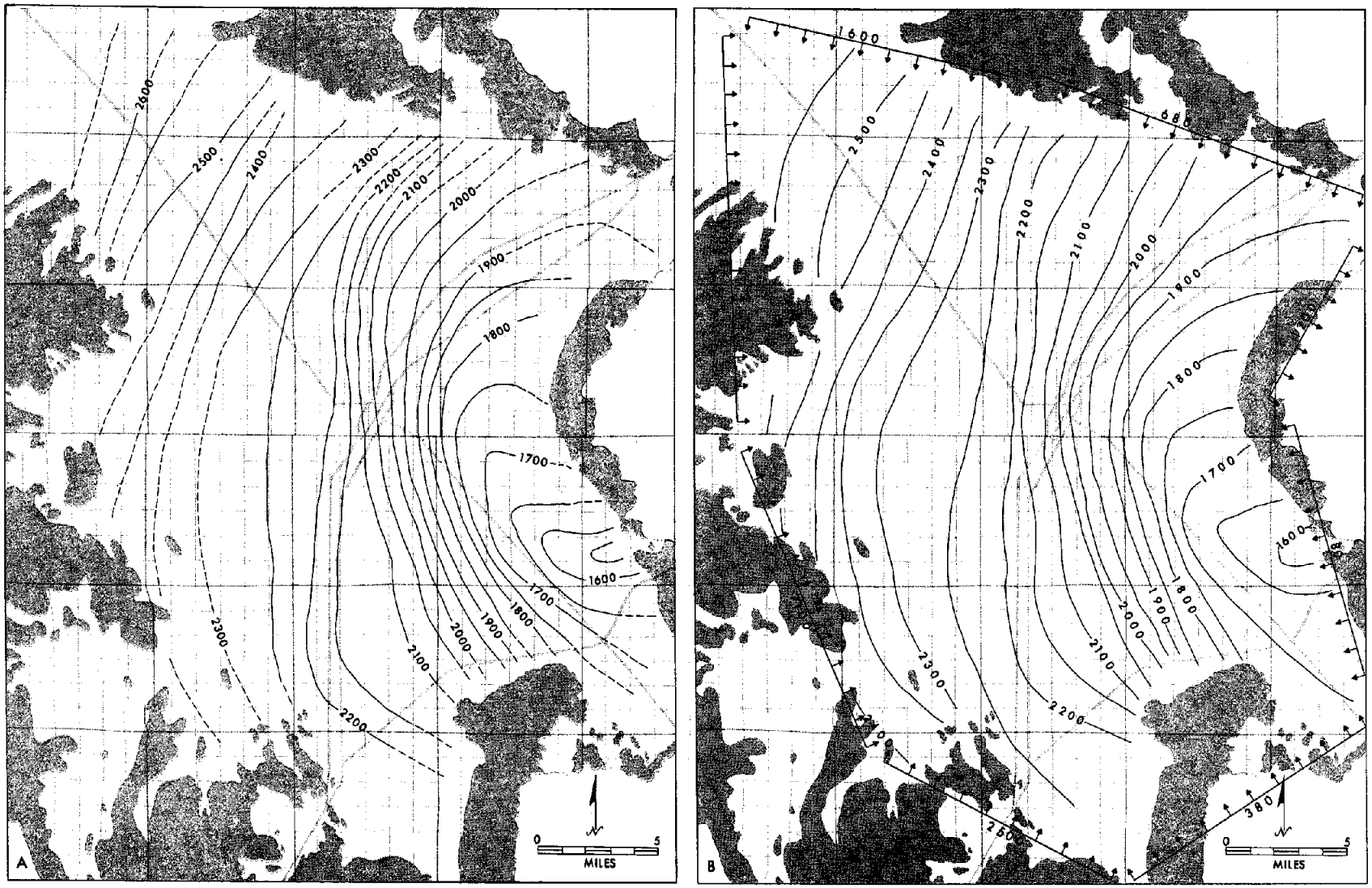
Figure 23B also shows about 1,200 acre-feet per year of subsurface outflow along the east side of the valley in the southern part of T. 19 S. and in T. 20 S. This amount of outflow was needed to obtain a satisfactory agreement between observed and simulated potentiometric surfaces. The following statements regarding ground-water flow in this part of the area were made by Loeltz (1963, p. Q5):

> "Data for the area near Lake Mead Base and Nellis Air Force Base are insufficient for accurate mapping of the direction of ground-water movement, but it is inferred to be southeastward beneath the military bases toward Frenchman Mountain.
>
> "Whether some or all of the ground water in the Lake Mead Base area moves southwestward into Frenchman Mountain is not known. The possibility of movement into the mountain is recognized because the contours on the piezometric surface, although insufficiently controlled, infer such movement, and the nature and structure of the rocks do not preclude movement of water through them."

Results of this study strongly imply subsurface outflow in this area. Although outflow of the magnitude indicated (1,200 acre-ft/yr) has a significant effect on the local ground-water flow regimen, it amounts to less than 5 percent of the ground-water budget under natural conditions and thus has only minor effects on the overall flow regimen of the valley.

Response to Development Before 1955

Changes which occurred as a result of development prior to 1955 are not directly within the scope of this study; however, simulation of the response during this period provides additional verification of the degree



EXPLANATION

Valley-fill

Consolidated rocks

Contact

Basin boundary

60

Potentiometric contour, shows altitude at which water level would have stood in tightly cased wells perforated in the principal aquifers. Dashed where approximately located. Contour interval 50 feet. Datum is mean sea level

Central part of area after Malmberg (1965, pl. 7). Other areas approximated by author based on available data

EXPLANATION

Valley-fill

Consolidated rocks

Contact

Basin boundary

2200

Simulated potentiometric contour, shows altitude at which water level would have stood in tightly cased wells perforated in the principal aquifers. Contour interval 50 feet. Datum is mean sea level

380

Quantity of recharge or discharge into bedrock, (in parenthesis), used in simulation of the natural system. In acre-feet per year

Figure 23.--Contours of potentiometric surface under natural conditions. A. From field data. B. Simulated by model.

to which the model can reproduce changes in the natural system. The 40-year interval 1915-54 was divided into four 10-year pumping periods. Water was pumped at a rate approximately equal to the average annual pumpage for each period. Distribution of early pumpage was based on available information, which is somewhat sparse. The following list summarizes the pumpage data used:

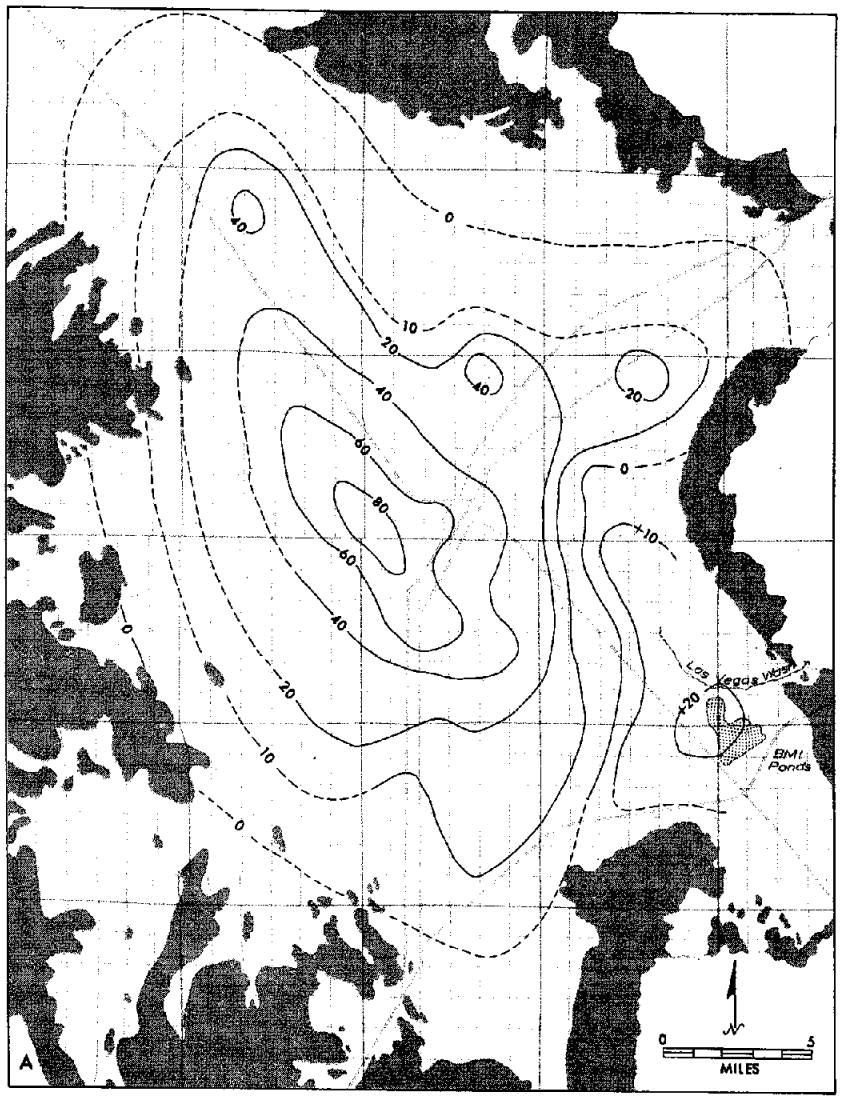
Pumping period	Period		Number of nodes used as pumping centers	Average annual pumping rate (acre-feet)
	From	Through		
1	1915	1924	20	15,000
2	1925	1934	30	17,000
3	1935	1944	39	19,000
4	1945	1954	91	32,000

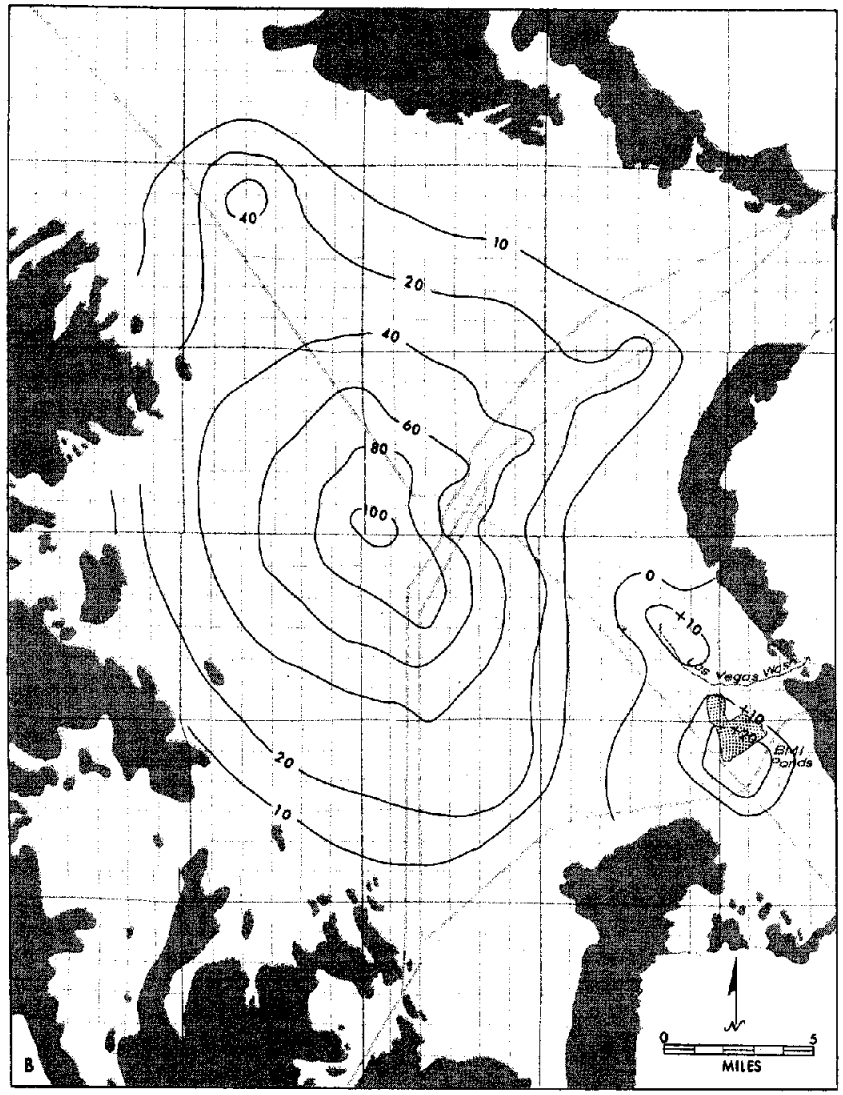
Total pumpage from the principal aquifers was about 830,000 acre-feet for the 40-year period. During the last pumping period (1945-54), a net rise in head was observed in the principal aquifers in the southeast part of the valley (Malmberg, 1965, pl. 6). This was due primarily to two causes: (1) Seepage from BMI ponds, which locally caused the water table to rise until vertical gradients were reversed and downward leakage occurred; and (2) a water-table rise adjacent to parts of Las Vegas Wash, which locally reduced vertical head gradients and consequently reduced upward leakage. Because head in the near-surface reservoir was assumed to be constant in the model, the net rise could not be simulated by considering downward leakage. As an alternative, water was recharged into the principal aquifers at selected nodes near the ponds and along the wash. The rate of recharge was varied until reasonable agreement between observed and simulated changes was obtained. A good agreement was obtained when about 2,400 acre-feet per year was recharged to the system. Of this total, about 1,500 acre-feet was recharged near the BMI ponds (much larger quantities of water infiltrate from the ponds to the ground-water system, but only 1,500 acre-feet per year appears to circulate deep enough to recharge the principal aquifers). Areas where ground water was recharged to the system are shown on plate 1.

Figure 24 shows (A) the observed net change in water levels from natural conditions to the spring of 1955 and (B) the simulated net change for the same period. The simulated and observed changes are in generally good agreement; however, a perfect match does not exist. This may be due in part to the comparatively long pumping periods used to approximate the actual pumpage, which increased from about 15,000 to 36,800 acre-feet per year during this 40-year period (Malmberg, 1965, p. R63), and in part to the inability of the model to simulate a complex natural system.

Response to Development During 1955-72

The 18-year period 1955-72 was simulated in more detail than the previous 40 years. The study period was divided into nine pumping intervals. Nine intervals were considered the minimal number of steps needed to approximate variations in pumpage that occurred during the 18-year period. Results were grouped and analyzed for the longer intervals 1955-62, 1963-72,





EXPLANATION

Valley-fill

Consolidated rocks

Contact

Basin boundary

2200

Line of equal net water-level change. Lines indicate water-level decline, except where rise is signified by "+". Dashed in areas of little or no data. Intervals are 10 and 20 feet

Lines are the approximate sum of changes shown by Malmberg, 1965, pl. 6, and Domenico and others, 1964, fig. 24

Figure 24.--Net change in water levels, natural conditions to 1955.

EXPLANATION

Valley-fill

Consolidated rocks

Contact

Basin boundary

60

Line of equal simulated net water-level change. Lines indicate water-level decline, except where rise is signified by "+". Intervals are 10 and 20 feet

From field data. B. Simulated by model.

and 1955-72, which are comparable with estimates in table 8. Figures 9 and 10 show the distribution of total pumping at the beginning and end of the study period. A similar distribution for the principal aquifers was prepared for each pumping interval. Pumping rates used in the model are those estimated for the principal aquifers (table 2). The following list summarizes pumpage data used in the simulation:

Pumping period	Period From	Period Through	Number of nodes used as pumping centers	Average annual pumping rate (acre-feet)
1	1955	1958	91	42,000
2	1959	1961	89	47,000
3	Spring 1962	Fall 1962	74	a (60,000)
4	Fall 1962	Winter 1963	72	a (26,000)
5	1963	1967	100	69,000
6	1968	1970	121	82,000
7		1971	121	81,000
8	Spring 1972	Fall 1972	122	a (70,000)
9	Fall 1972	Winter 1973	125	a (37,000)

a. Rates for these periods are seasonal pumping rates. Average annual rate for 1962 was 52,000 acre-feet and average annual rate for 1972 was 62,000 acre-feet.

Table 8.--*Summary of simulated storage depletion and leakage for 18-year period 1955-72*

(All quantities in acre-feet, rounded to two places.)

Item	1955-62	1963-72	Total 1955-72
Storage depletion:			
Principal aquifers	130,000	295,000	420,000
Consolidated rock	10,000	25,000	35,000
Subtotal	140,000	320,000	460,000
Leakage through near-surface reservoir:			
Inflow to principal aquifers (downward leakage) 1/	77,000	180,000	260,000
Discharge (upward leakage)	120,000	100,000	220,000

1. Includes about 2,400 acre-feet per year in southeast end of valley derived from Lake Mead.

Two years, 1962 and 1972 (the years at the beginning and end of the 10-year budget period) were divided into two pumping periods so that seasonal variation in the magnitude and distribution of pumping could be taken into account. Seasonal variations in 1962 were based on monthly water demands for the period 1958-61 (Domenico and others, 1964, fig. 14). Seasonal variation in 1973 was based on monthly records of pumpage reported by the Las Vegas Valley Water District and the City of North Las Vegas.

Rising water levels in the southeast part of the valley were simulated in the same manner as for the period prior to 1955.

Figure 25 shows the simulated net change in potentiometric surface during the period February 1955-February 1973 in response to pumpage from the principal aquifers for the period 1955-72 1/ (table 3). Figure 26 shows the simulated net change in potentiometric surface of the principal aquifers for the period 1963-72 1/ (table 3). The magnitudes and distribution of the computed drawdowns are comparable with the observed drawdowns shown in figures 11 and 13. Although general agreement is obtained, the match is not perfect due to unresolved hydrologic factors and limitations of the model. The storage depletions represented by this evaluation are shown in table 9.

Hydrographs showing both observed and computer-generated data were prepared for eight wells that penetrate the principal aquifers (figs. 27 and 28). Well locations are shown in figures 25 and 26. These hydrographs provide additional information concerning the degree to which the model was able to simulate the natural system.

Plate 1 shows the simulated distribution of leakage during 1955, 1962, 1971, and 1972, and the estimates are summarized in table 8. Estimates of leakage during the 18-year period were made by interpolating between the values shown on plate 1. Table 9 lists the annual estimates of upward leakage, total downward leakage, and downward leakage in areas where the water table did not decline during the study period. The last quantity mentioned gives an estimate of the minimal amount of secondary recharge that has reached the principal aquifers. The quantity is probably greater than the numbers listed in the table because secondary recharge is probably also occurring in some places where water levels are declining in the near-surface reservoir; however, this quantity cannot be determined from existing data. Thus, the total amount of secondary recharge that reached the principal aquifers during the period 1955-72 probably exceeds 84,000 acre-feet, but is substantially less than 200,000 acre-feet. The minimal value of 84,000 acre-feet is used for purposes of this report. This

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1. Net changes in water levels are based on measurements made when levels are least affected by pumping, which usually is in the late winter of each year. Thus, the measurements in February 1973 largely reflect the affects of pumping during the previous spring, summer, and fall (1972). For the 18-year period February 1955 to February 1973, the net affects of seasonal pumping during the years 1955-72 inclusive are evaluated by the model.

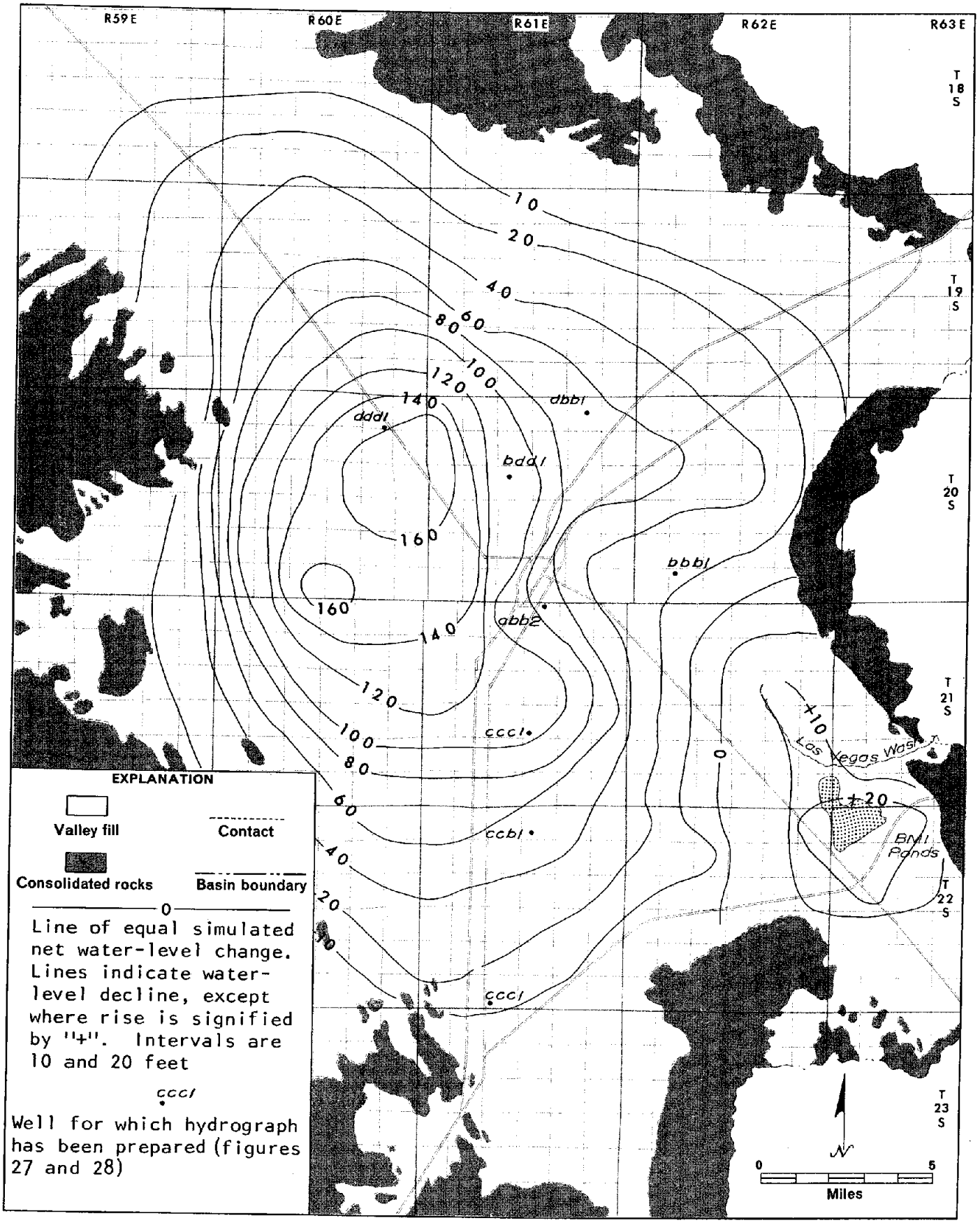

Figure 25.--Simulated net change in water levels, principal aquifers, February 1955-February 1973.

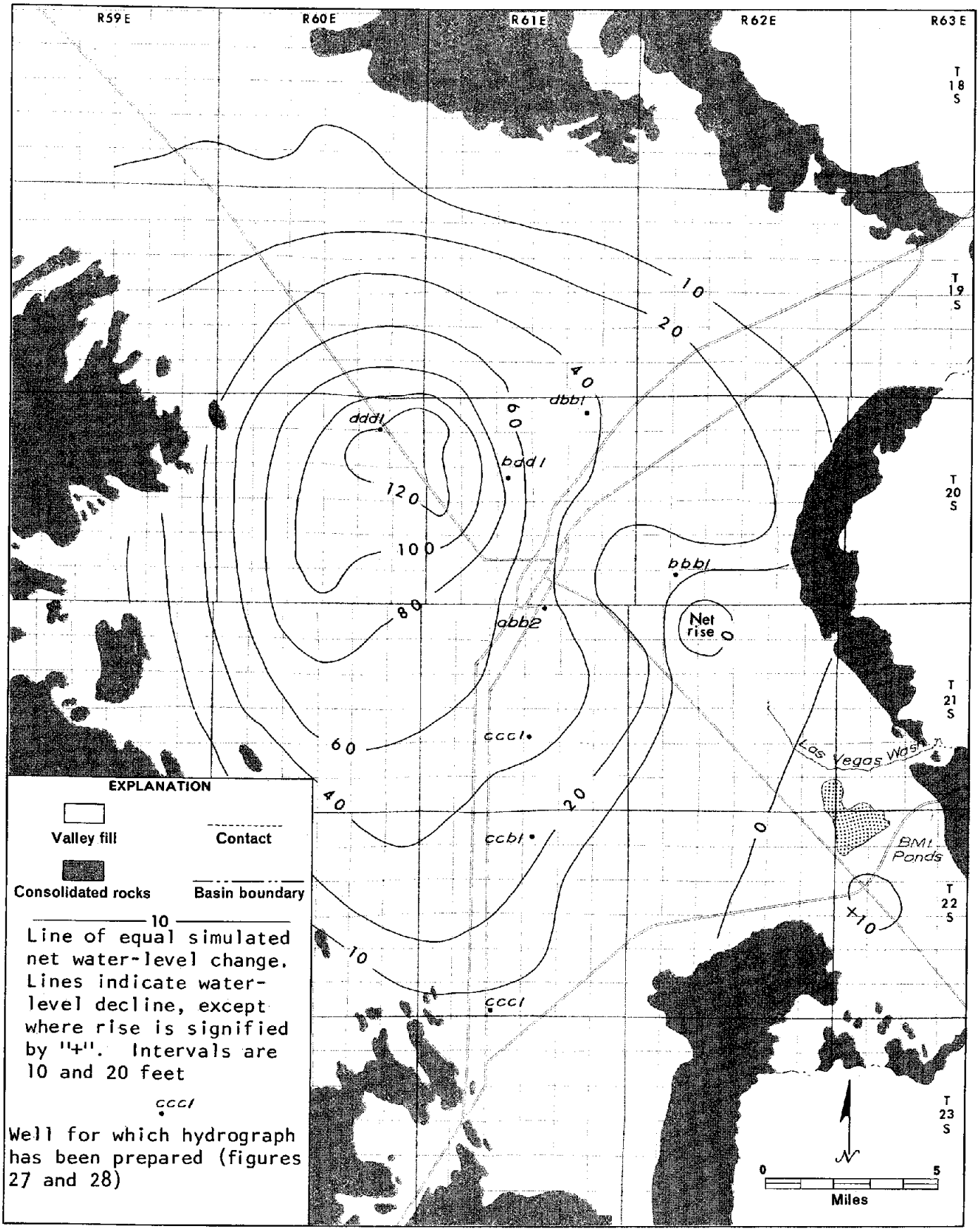

Figure 26.--Simulated net change in water levels, principal aquifers, February 1963-February 1973.

Table 9.--*Summary of leakage estimates for 1955-72, based on simulation of flow system*

(All values in acre-feet, rounded to two significant numbers)

Year	Upward leakage	Downward leakage	
		Total 1/	In areas of no net water-level decline in near-surface reservoir 2/
1955	17,000	4,200	2,800
1956	16,000	5,100	3,000
1957	16,000	6,000	3,200
1958	15,000	6,700	3,400
1959	14,000	7,600	3,600
1960	14,000	8,400	3,800
1961	13,000	9,300	4,000
1962	12,000	10,000	4,300
1963	12,000	11,000	4,500
1964	11,000	12,000	4,800
1965	11,000	14,000	5,200
1966	10,000	15,000	5,500
1967	10,000	16,000	5,800
1968	9,700	17,000	6,100
1969	9,300	18,000	6,400
1970	8,900	20,000	6,800
1971	8,600	21,000	7,200
1972	11,000	13,000	4,100
Totals	220,000	210,000	84,000

1. Does not include about 2,400 acre-feet per year in southeast end of valley imported from Lake Mead water.
2. Provides rough estimate of minimal quantity of secondary recharge.

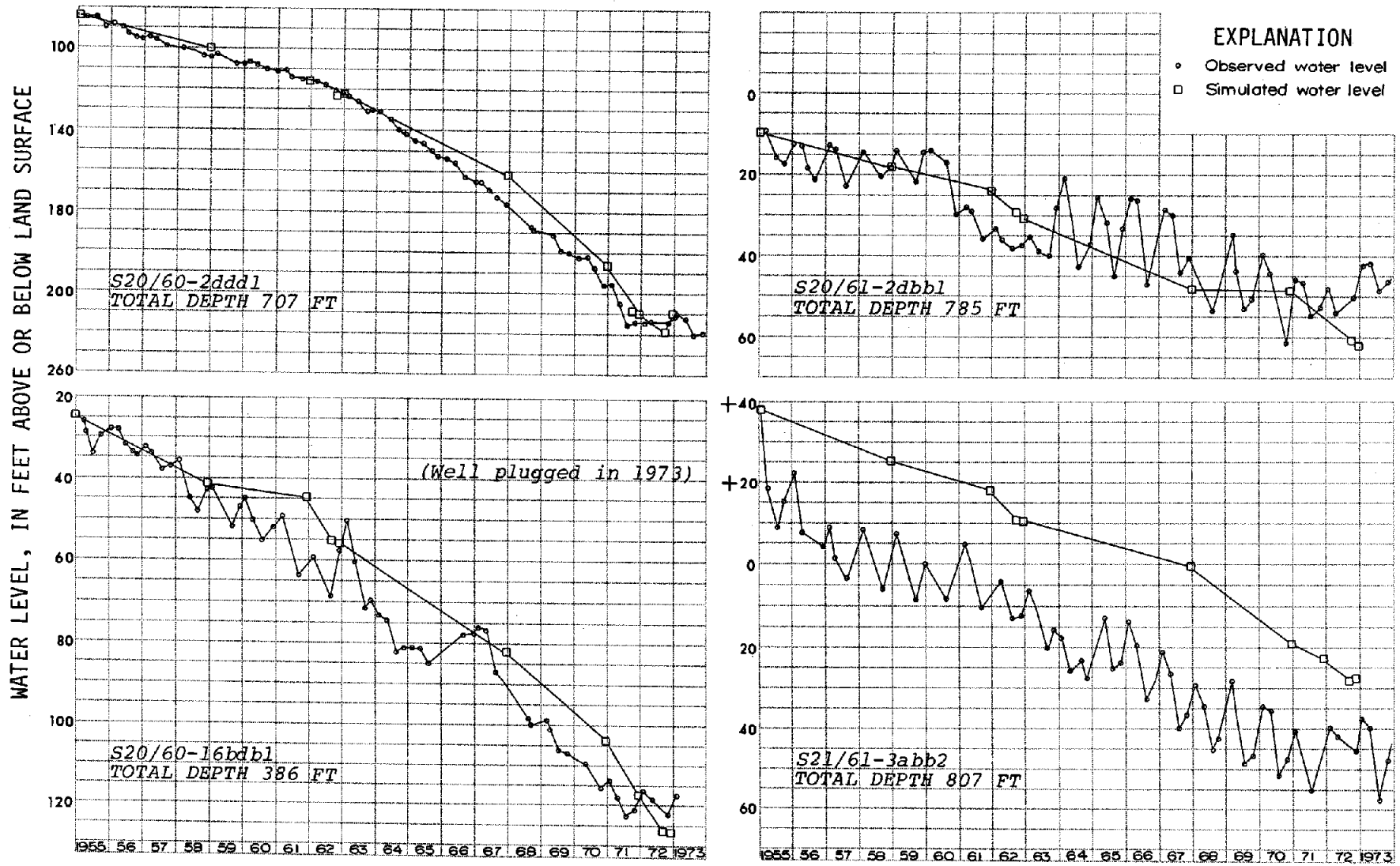

Figure 27.--Water-level changes during 1955-73, in four wells in northern Las Vegas Valley.

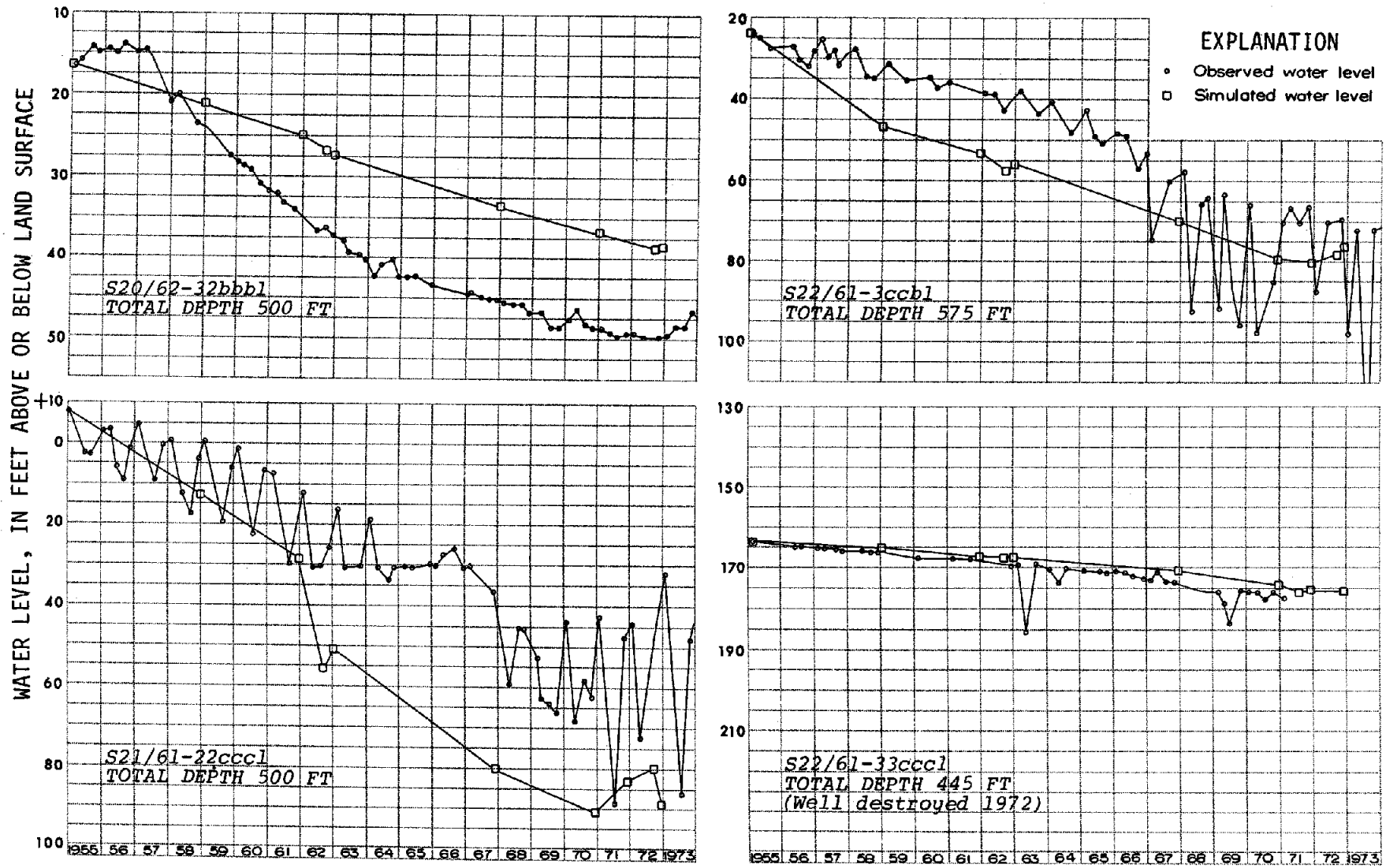

Figure 28.--Water-level changes during 1955-73, in four wells in southern Las Vegas Valley.

figure should be revised when the relationship between the near-surface reservoir and the principal aquifers is better understood. Moreover, this quantity does not include recharge of Lake Mead water in the southeastern part of the valley, which has already been discussed.

Changes in the magnitude and distribution of leakage between the near-surface reservoir and principal aquifers are shown on plate 1. The areas of upward and downward leakage shown on plate 1 agree favorably with areas of water-level rise and decline shown in figures 11-14. The general trend of leakage is an increasing area and magnitude of reverse (downward) flow in response to increased pumping. This trend was temporarily interrupted in 1972 when pumping was reduced by 15,000 acre-feet as the Southern Nevada Water Project became operational. As of 1975, distribution and storage facilities for the first stage of the project had reached capacity and additional demands for water were being met by pumping ground water. Consequently, the area and magnitude of downward flow has probably increased since 1974. Secondary recharge to the principal aquifer, exclusive of recharge from BMI tailings ponds and Las Vegas Wash, has increased from about 4,100 acre-feet in 1972 to about 10,000 acre-feet per year in 1974.

GROUND-WATER BUDGET

Principal Aquifers

Table 10 is a ground-water budget which summarizes the various items of inflow to and outflow from the principal aquifers during the 18-year period 1955-72. The imbalance between estimates of recharge and discharge agrees closely with computations of storage depletion generated by the model. It is also within the general range indicated by estimates based on water-level changes.

Near-Surface Reservoir

A complete ground-water budget that would include all the pertinent information about the near-surface reservoir is beyond the scope of this study. The largest unresolved items are the quantity of secondary recharge to the shallow system and the resulting effect of secondary recharge on storage and discharge in the central and lower parts of the valley. Although no budget was constructed for the near-surface reservoir, the estimated storage depletion from table 7 is as follows:

Period	Provisional estimate
1955-62	59,000 acre-feet
1963-72	71,000 acre-feet
1955-72	130,000 acre-feet

These estimates may be roughly checked by comparing them with leakage data generated by the model. Table 9 shows a total downward leakage of 210,000 acre-feet during the period 1955 -72. Of this amount, about 84,000 acre-feet occurred where secondary recharge to the near-surface reservoir was

Table 10.--*Ground-water budget, principal aquifers, 1955-72*

(All figures in acre-feet)

Item		Period 1955-62	1963-72	1955-72
RECHARGE:				
Natural recharge (p. 49)		240,000	300,000	540,000
Downward leakage (table 8)		77,000	180,000	260,000
Subsidence (p. 41) 1/		28,000	40,000	68,000
Total (rounded)	(1)	350,000	520,000	870,000
DISCHARGE				
Pumpage (table 3)		360,000	730,000	1,090,000
Upward leakage (table 8)		120,000	100,000	220,000
Subsurface outflow (p. 50)		10,000	12,000	22,000
Total (rounded)	(2)	490,000	840,000	1,330,000
STORAGE DEPLETION:				
A. Computed: recharge (1) minus discharge (2)		-140,000	-320,000	-460,000
B. Estimated from water-level changes (table 7)		-200,000	-270,000	-470,000
C. Estimate generated by model (table 8)		-140,000	-320,000	-460,000
Maximum difference between methods		60,000	50,000	10,000
Maximum difference between methods as a percentage of pumpage		17	7	1

1. Estimated total volume from field data. Leakage computations include some water removed from storage in confining beds during subsidence, so some water may be counted twice.

sufficient to prevent any decline in the water table. The net quantity of 126,000 acre-feet provides a rough indication of the magnitude of storage depletion in the near-surface reservoir.

Estimates based on water-level changes may be in error due to error in the assigned storage coefficient, and estimates based on leakage may be in error because the simplifying assumptions used in the model probably do not represent the complex flow relationships in the near-surface reservoir. Consequently, these estimates are provisional and serve only to identify the approximate magnitude of storage depletion. They should be revised when more information is available about cause-and-effect relationships in the near-surface reservoir.

OVERDRAFT

When a previously stable ground-water system is developed, pumped water is withdrawn from storage until resulting water-level declines alter the flow system sufficiently to either reduce the outflow or induce inflow. Eventually water levels stabilize and the system approaches a new equilibrium where pumpage plus the reduced natural discharge (the quantity can be reduced to zero) equals the natural recharge plus any additional recharge induced as a result of development

If ground water is withdrawn from a source more rapidly than it is being replenished an overdraft develops. Ultimately, resulting water-level declines normally cause pumping costs to become prohibitive.

Two generalized types of overdraft are possible: basinwide and localized. Basinwide overdraft occurs when net ground-water pumpage exceeds inflow to the ground-water system over a sustained period of time. In this case, water levels will continue to decline as long as pumping is maintained, although the rate of decline will decrease as natural discharge is captured by pumping. Thus, even though wells may be ideally located, cumulative effects of gradual but sustained water-level declines will eventually result in excessive pumping costs or other undesirable effects. At this point, either additional water must be imported or pumpage must be reduced. A more common occurrence in Nevada valleys is localized overdraft, which results from pumping being concentrated in a localized area. Water-level declines in these areas are accelerated and pumping lifts and associated detrimental effects, such as land subsidence, may become intolerable before enough discharge is captured to offset the pumping and stabilize water levels.

In Las Vegas Valley, a basinwide overdraft has existed for many years. Malmberg (1965, p. 84) estimated that in 1955 the overdraft on the principal aquifers was about 23,000 acre-feet and that there was no discernible overdraft on the near-surface reservoir. Moreover, pumping then and in 1975 was concentrated along the west-central side of the valley, where the most productive aquifers have been tapped by wells. Accelerated water-level declines in the west-central part of the valley probably will result in a local overdraft long before significant quantities of discharge are captured or appreciable secondary recharge (to the principal aquifers) is induced from the south-central and southeastern parts of the valley.

Table 11 summarizes the estimated overdraft as of 1974. A perennial yield of 25,000 acre-feet per year (Malmberg, 1965, p. 90) was used instead of the estimated recharge of about 30,000 acre-feet per year as developed in this study. The more conservative value was chosen because of uncertainties involved in the capture of subsurface outflow through unconsolidated rock, constraints posed by subsidence problems in the central part of the valley, and the presence of poor quality water in the southeastern part of the valley. Pumpage in 1974 was almost twice the pumpage in 1955; however, the increased area and magnitude of downward leakage in 1974 resulted in a secondary recharge to the principal aquifers of roughly 10,000 acre-feet compared to only about 3,000 acre-feet in 1955 (table 9). Overdraft on the principal aquifers in 1974 was on the order of about 36,000 acre-feet.

Table 11.--*Estimated magnitude of overdraft in principal aquifers, 1974*

Item		Acre-feet
Perennial yield (Malmberg, 1965, p. 90)		25,000
Secondary recharge (p. 61)		10,000
Subtotal	(1)	35,000
Pumpage from principal aquifers (table 3)	(2)	71,000
Approximate overdraft: (1) - (2)		36,000

Future declines in water levels and increased deep percolation from lawn watering in new home tracts along the west flank of the valley will increase secondary recharge and thereby augment the perennial yield of the principal aquifers. However, increases in secondary recharge due solely to these factors probably will not be adequate to alleviate local overdraft in the west-central part of the valley. Eventually, active measures may be required. An example is the pilot recharge project proposed by the Las Vegas Valley Water District.

SUMMARY AND CONCLUSIONS

Table 12 summarizes the various quantitative estimates developed during this study. The principal conclusions regarding the ground-water reservoir in Las Vegas Valley are as follows:

1. The analysis of the natural system made in this study indicates that recharge is about 30,000 acre-feet per year, which is in reasonable agreement with estimates of natural recharge and discharge made by previous investigators (range of estimates, 25,000 to 35,000 acre-feet per year). Results from model simulation of the natural flow system indicate that some subsurface outflow from the valley occurs in the vicinity of Frenchman Mountain. The estimate of 1,200 acre-feet per year is accurate enough to identify the general magnitude of the outflow, but may need to be revised when more data are available.

Table 12.--*Summary of hydrologic estimates*

(Water estimates in acre-feet)

Item	Study periods 1955-62	1963-72	1955-72
Level of development			
Pumpage			
Principal aquifers	360,000	730,000	1,090,000
Near-surface reservoir	10,000	40,000	50,000
Total	370,000	770,000	1,140,000
Imported water	150,000	320,000	470,000
Response to pumping			
Principal aquifers			
Storage depletion (exclusive of subsidence)			
A. Estimate from water budget	140,000	320,000	460,000
B. Estimate from observed water-level changes	200,000	270,000	470,000
C. Estimate from model	140,000	320,000	460,000
Subsidence	28,000	40,000	68,000
Upward leakage	120,000	100,000	220,000
Downward leakage			
Supplied by secondary recharge:			
At south end of valley 1/	19,000	24,000	43,000
Remainder 1/	28,000	56,000	84,000
Removed from storage 1/	29,000	97,000	130,000
Total (rounded)	76,000	180,000	260,000
Near-surface reservoir			
Storage depletion 1/	59,000	71,000	130,000
Consolidated rocks			
Storage depletion 1/	10,000	25,000	35,000

1. Accuracy of these estimates slightly less than others in this table.

2. During the period 1955-74, pumped ground water was the principal source of water supply for Las Vegas Valley. Annual pumpage increased from 40,000 acre-feet in 1955 to a maximum of 88,000 acre-feet in 1968. Slight decreases occurred through 1971. In 1972, the first year of full operation of the Southern Nevada Water Project, annual pumpage dropped from 85,000 to 70,000 acre-feet. It remained at 70,000 acre-feet in 1973. By 1974, distribution and storage facilities available to handle imported water were operating at near capacity, and demands for additional water were met by ground water; annual pumpage increased to 78,000 acre-feet. The total amount of imported water increased from 16,683 acre-feet in 1955 to 41,089 acre-feet in 1971 and 75,455 acre-feet in 1974.

3. Substantial water-level declines have occurred along the west side of the valley because of heavy pumping from high-yield aquifers there. Little or no decline has occurred in the south-central and south-eastern parts of the valley. The maximum net decline measured between February 1955 and February 1973, about 180 feet, occurred near centers of heavy pumping in T. 20 S., R. 60 E. Reductions in pumping in 1972-73 resulted in a temporary recovery of water levels. However, the pumping rate remained high and annual pumpage began to increase again in 1974. Consequently, as of March 1975, annual water-level declines in the principal aquifers exceeded 10 feet per year in an area of nearly 25 square miles on the west side of the valley.

4. Land subsidence continues in Las Vegas Valley. Subsidence associated with heavy pumping in the central part of the valley became a serious problem in the early 1960's. After about 1963, some pumping was relocated to high-yield wells in gravel aquifers in the northwestern part of the valley. This relocation helped alleviate subsidence problems to some degree in the central part of the valley, but still the maximum observed subsidence from 1963 through 1972 was about 2 feet in the vicinity of Craig Road about a mile east of the Tonopah Highway in T. 20 S., R. 60 E. The estimated volume of compaction resulting from subsidence during the period 1955-72 was about 68,000 acre-feet. Equating the volume of compaction to the volume of water squeezed from compacted deposits, this amounted to about 6 percent of the total pumpage during the same period.

5. Pumping during the period 1955-72 has resulted in storage depletions of about 470,000 acre-feet from the principal aquifers, about 130,000 acre-feet from the near-surface reservoir, and about 35,000 acre-feet from consolidated rocks which border the valley-fill reservoir. Storage depletion from all sources (including water derived from subsidence) amounted to about 700,000 acre-feet, or 61 percent of the total pumpage during the period.

6. Pumpage not derived from storage was supplied by the capture of springflow and upward leakage, and from secondary recharge that consists mainly of infiltration from lawns, golf courses, and irrigated land. During the period 1955-73, reductions in spring discharge totaled about 110,000 acre-feet, reductions in upward leakage totaled about 230,000 acre-feet, and secondary recharge to the principal aquifers was about 120,000 acre-feet.

7. The findings of this study agree closely with estimates of the annual natural recharge of 25,000 acre-feet per year made by Malmberg (1965, p. 90) and considered to be a conservative estimate of the perennial yield. This study suggests that natural recharge may be about 30,000 acre-feet per year; however, uncertainties involved in the capture of subsurface outflow, and constraints on development posed by subsidence problems in the central part of the valley and areas of naturally occurring poor-quality water in the southeastern part of the valley, support the more conservative value of 25,000 acre-feet per year.

8. The perennial yield of the natural system has been augmented by secondary recharge. As of 1974, substantial secondary recharge to the near-surface reservoir occurred in the central and southeastern parts of the valley; however, only part of this recharge percolated deeply enough to replenish the principal aquifers. Secondary recharge to the principal aquifers in 1974 was about 10,000 acre-feet. Thus, disregarding possible long-term changes in water quality, the valley-fill reservoir could yield about 35,000 acre-feet per year on a sustained basis under 1974 conditions.

9. Overdraft on the principal aquifers in 1974 was about 36,000 acre-feet. Continued water-level declines probably will induce additional secondary recharge which may help to partly alleviate future overdrafts. Concentrated pumping along the west-central part of the valley has accelerated water-level declines. A severe local overdraft probably will develop in this area long before significant discharge is captured or secondary recharge is induced from wet areas in the central and southeastern part of the valley. This condition may be alleviated somewhat by additional secondary recharge from new housing developments along the west side of the valley, and by active measures such as artificial recharge.

10. Ground water has been a major factor in the overall development of the valley to date, and undoubtably will continue to play an important role in the future. The historically high pumping rates have resulted in a significant overdraft on the valley-fill reservoir which, if allowed to continue unchecked, would ultimately result in uneconomic pumping lifts and severe subsidence problems. The general plan for the future is to increase imports until imported water becomes the primary source in the valley. At that time, ground-water pumpage can be adjusted so that the valley-fill reservoir can be managed more nearly on a sustained-yield basis with annual withdrawals on the order of 50,000 acre-feet which equals the amount currently being withdrawn under nonrevokable ground-water rights. The second phase of the Southern Nevada Water Project is not scheduled for completion until 1980. Consequently, overdraft on the ground-water reservoir may continue until sometime into the 1980's. The sustained yield possible at that time will depend on the extent to which the perennial yield can be supplemented by secondary recharge. This in turn would depend largely on the success of artificial-recharge projects which are proposed but not yet operational and on the success of efforts to maintain acceptable water quality. No firm estimate of the future sustained yield of the reservoir can be made until data on these projects are available; however, it should be significantly greater than the 35,000 acre-feet per year considered possible as of 1974.

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STATE OF NEVADA
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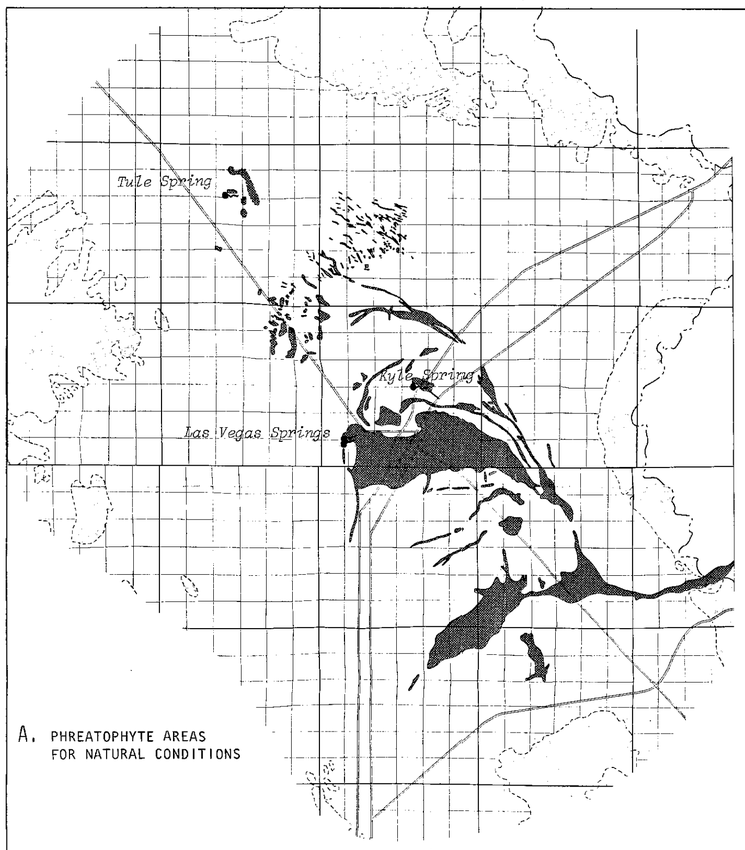
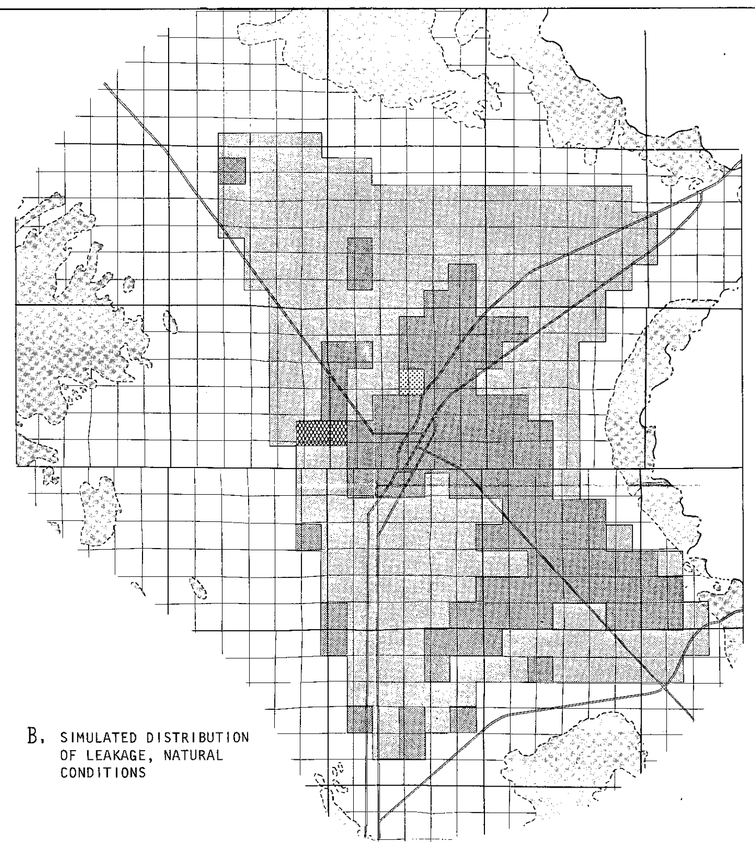
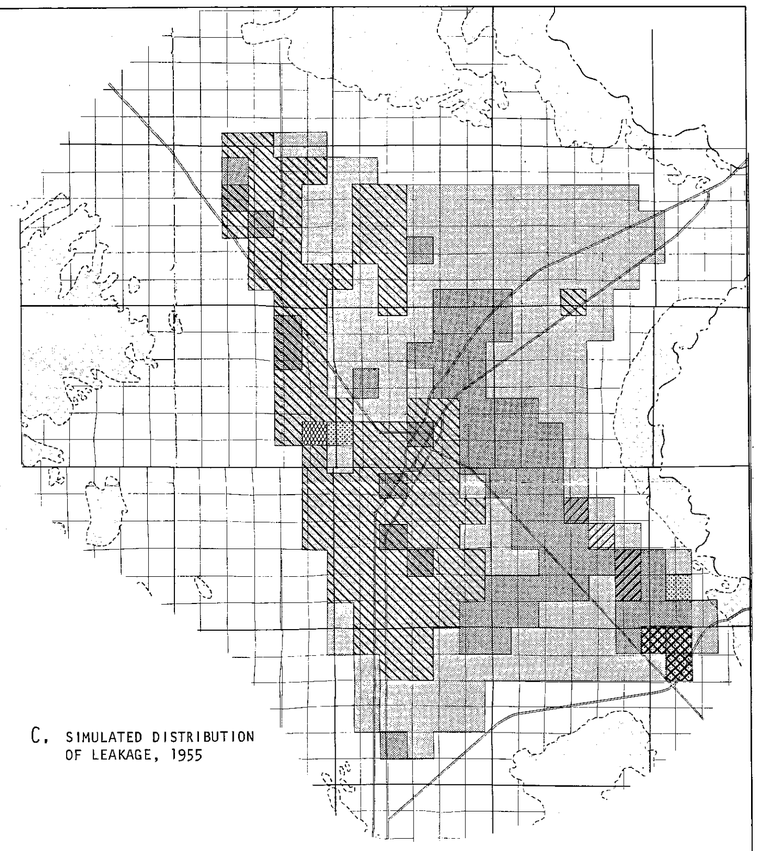
DIVISION OF WATER RESOURCES



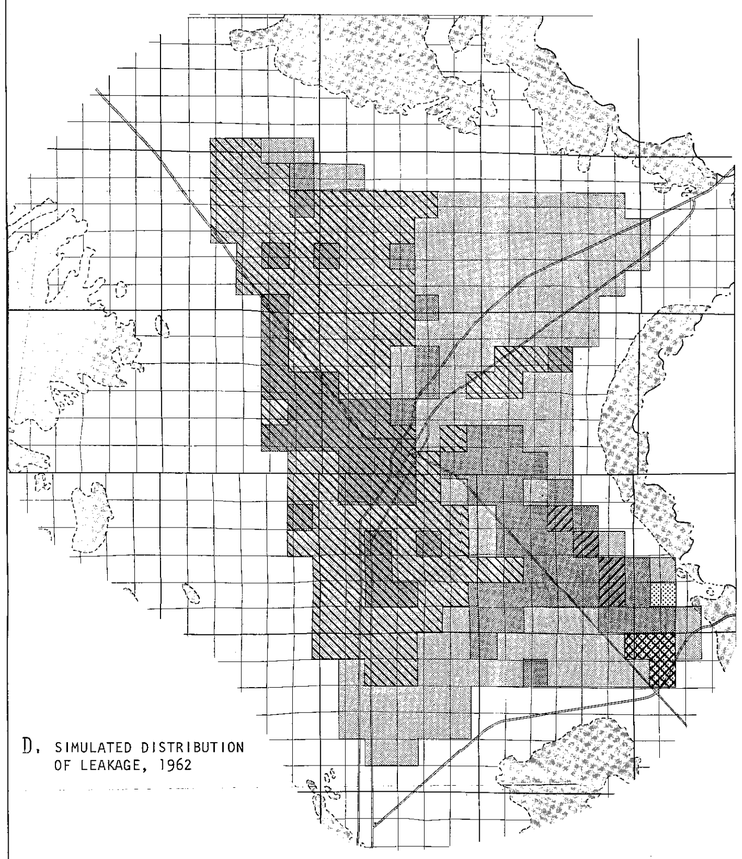
A. PHREATOPHYTE AREAS FOR NATURAL CONDITIONS



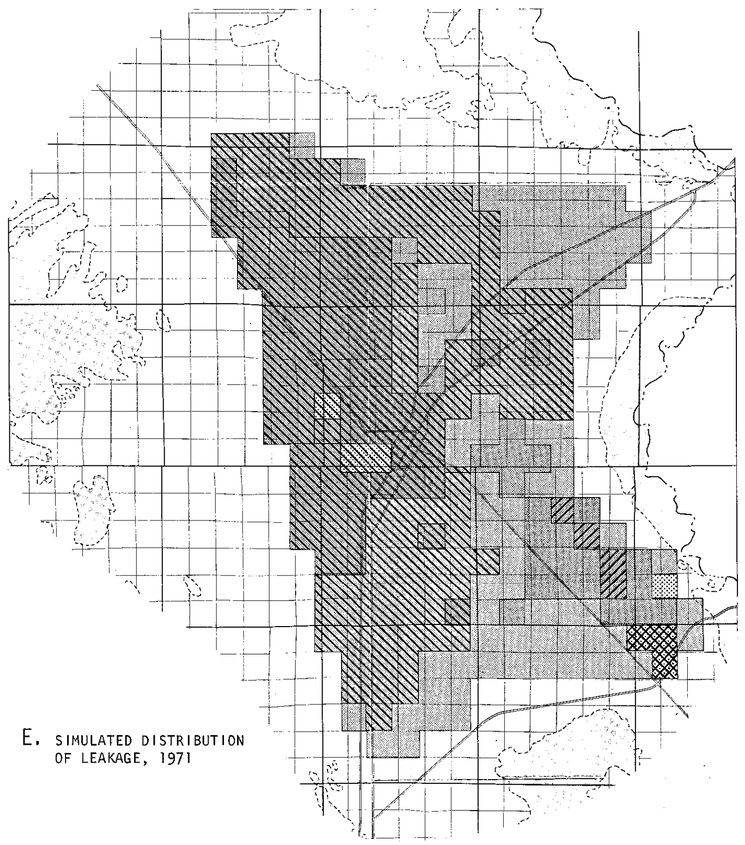
B. SIMULATED DISTRIBUTION OF LEAKAGE, NATURAL CONDITIONS



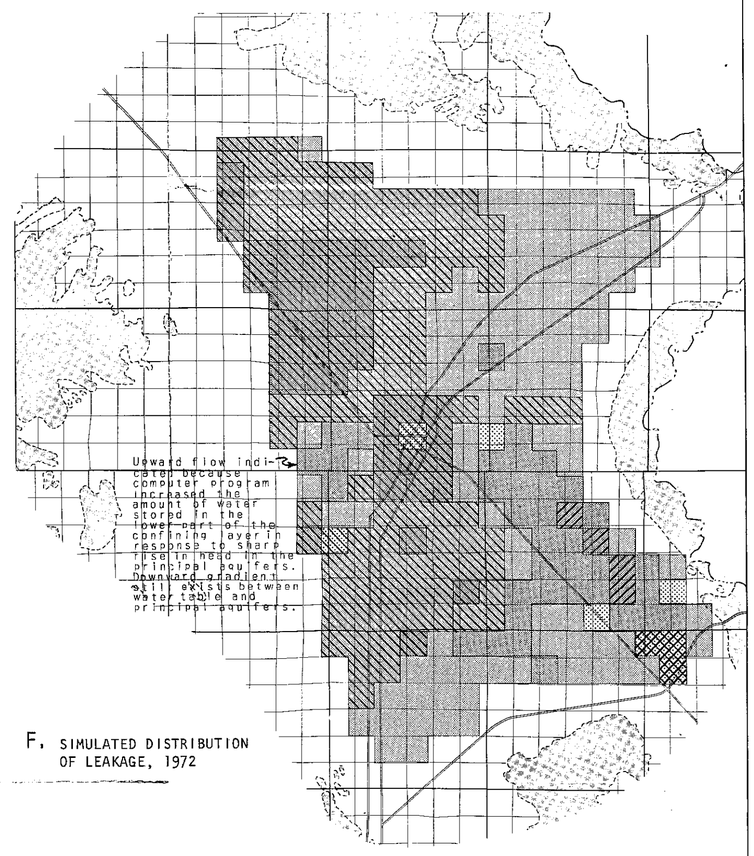
C. SIMULATED DISTRIBUTION OF LEAKAGE, 1955



D. SIMULATED DISTRIBUTION OF LEAKAGE, 1962



E. SIMULATED DISTRIBUTION OF LEAKAGE, 1971



F. SIMULATED DISTRIBUTION OF LEAKAGE, 1972

EXPLANATION

Valley fill

Consolidated rocks

Contact

Basin boundary

LEAKAGE (feet/year)

Down	Up
	<0.1
	0.1-0.5
	0.5-1.0
	>1.0

PHREATOPHYTE AREAS After Malmberg, 1965, pl. 10; some areas in T. 19 S. added by author

Node where additional water was introduced into system to simulate response to water-table rise in near-surface reservoir

YEAR	UPWARD LEAKAGE 1/ (AC-FT/YR)	DOWNWARD LEAKAGE (AC-FT/YR)
NATURAL CONDITIONS	29,000	NIL
1955	17,000	4,200
1962	12,000	10,000
1971	8,600	21,000
1972 A/	11,000	13,000

1. Includes spring discharge.

A. First full year of operation of Southern Nevada Water project. Annual pumpage reduced from 85,000 ac-ft in 1971 to 70,000 ac-ft in 1972.

0 5 MILES

Cartography by Marj Thielke

PLATE 1.--DISTRIBUTION OF PHREATOPHYTES AND SIMULATED DISTRIBUTION OF VERTICAL LEAKAGE.